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HEAD-UP DISPLAY STUDY

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Hughes Aircraft Company

Culver City, California

TECHNICAL REPORT AFAL-TR-73-215

July 1973

Air Force Avionics Laboratory

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HEAD-UP DISPLAY STUDY

E.W. OPITTEK

FOREWORD

This report covers the work accomplished during the period May 1972 through February 1973 under contract F33615-72-C-2140; Head-Up Display Study. The work was supported by the United States Air Force Avionics Laboratory (AFAL), Wright Patterson Air Force Base, Dayton, Ohio. The Technical Monitor was Mr. N. Kopchick of AFAL.

The work was accomplished by the Display Systems and Human Factors Department of Hughes Aircraft Company under the direction of Mr. E. W. Opittek who was Project Engineer. Special acknowledgement is given to the following individuals for contributions to this project.

Mr. J. Gunvordahl conducted the pilot interviews and summarized the interview results. Doctor D. Close of the Hughes Research Laboratory conducted the research and analysis of the Holographic Lens Combiner. Mr. L. A. Hendrix conducted the illumination source tradeoff and overall design configuration definition. He was also instrumental in defining the demonstrator configurations. Mr. M. N. Ernstoff provided valuable consultation on liquid crystal technology. Mr. J. B. Setto conducted the detailed design and supervised the construction of the advanced HUD demonstrator and mockup delivered as part of the program.

This technical report has been technically reviewed and is approved.

COZIER S. KLINE, Colonel, USAF
Chief, System Avionics Division
AF Avionics Laboratory

ABSTRACT

A study of the requirements for and the design of an advanced head up display was conducted. The requirements were based on the weapons and sensors aboard an advanced close air support all weather fighter aircraft. This analysis was supported by interviews with pilot users of head-up displays in the field. From this information, the following design goals were established:

Field of view	$60^\circ \times 45^\circ$
Resolution	1 mrad
Brightness/Contrast	1.8 against 10K fL background
TV raster capatible	

Existing conventional head up display techniques were evaluated with respect to meeting these requirements. It was concluded that such techniques (cathode ray tubes, conventional optics) could not be practically used to meet the field of view and brightness requirements. Accordingly, an advanced design utilizing holographic optics and liquid crystal display techniques was conceived and evaluated. This concept utilizes a holographic lens to provide the combiner and collimator functions. The liquid crystal matrix display provides modulation of the light from a collimated arc light source to provide either sensor or symbol video. Several alternate configurations using these components, capable of meeting the requirements, were derived. The A-10 aircraft was selected as a candidate for the installation due to its large canopy and over the nose visibility. One alternate configuration utilizes the curved canopy itself as the substrate for the holographic lens/combiner. As part of the study program, a demonstrator was developed to indicate how the holographic lens/combiner and reflective liquid crystal can be used together as a see through display. Also a half size mockup of the baseline cockpit configuration was fabricated. It is recommended that a feasibility model development program be undertaken to evaluate the performance of the advanced HUD concept.

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1.0 INTRODUCTION AND SUMMARY

1.1 Background

Advanced attack aircraft are planned for future USAF operations which will provide increased capability for close-air-support. New methods of computer guidance for low altitude, high-speed bomb delivery and the advent of trainable guns, utilizing computer aided pointing and tracking, are examples of the mission capability that is desired. Extending this operation to night attack, or to missions occurring under adverse weather is achieved with improved forward looking sensors such as low light level television or scanning IR sensors.

To achieve the necessary degree of safety and to insure survivability against hostile forces, the pilot must remain head-up for long periods throughout these missions, thus posing a critical requirement for head-up display (HUD) of weapon delivery information and cautionary status information concerning the condition of the aircraft. Furthermore, it is desirable for the pilot to receive electronic sensor information on possible ground threats such as radar homing and other active surveillance.

Existing head-up displays provide the pilot with essential flight control and weapon delivery information over a very limited visual angle and do so at a considerable weight penalty. Also, their brightness is less than adequate for the display of pictorial sensor information under the hazy bright conditions found in daylight operations during adverse weather such as ground fog or low cloud cover.

What is needed is a bright, wide field-of-view head-up display that will provide these functions at low weight and with reliability that is commensurate with advanced weapon system requirements.

1.2 Study Program

The HUD study program had three major objectives: (1) define the functional requirements of an advanced head-up display for use on attack aircraft in the 1980 time period, (2) determine the capabilities and limitations of existing technology in meeting these requirements and (3) define a baseline design approach for an advanced HUD technology to meet the requirements. The requirements for an advanced head-up display are analyzed in Section 2.0. Section 3.0 contains tradeoff of existing HUD technology and presents an advanced HUD concept which can be developed to meet the design requirements. The basic concept of the advanced HUD involves the use of holographic optics which provide both the collimation and the image combining function within a single thin-film element. Coupled with this is a new image source: the liquid crystal matrix display, which provides a reflective pictorial display uniquely suited to the holographic lens and one that is superior to the CRT for daylight operations. Sections 4.0, 5.0, and 6.0 describe the mechanization of these major components including illumination considerations for daylight and night operations. In Section 7.0, a baseline design configuration is presented in detail. Section 8.0 of this report outlines the future effort necessary to develop such a HUD.

1.3 Recommended Design

As a result of this study effort, a baseline design configuration was conceived which has evolved into a recommended advanced HUD configuration suitable for meeting the requirements of future USAF attack aircraft.

The baseline design is shown in Figure 1-1, which illustrates how the advanced head-up display can be integrated into an aircraft cockpit. A flat holographic lens combiner is supported in the pilot's forward field of view by the canopy structure. The symbology (or sensor video) to be displayed is projected upon the combiner by means of a relay lens which could be constructed from simple spherical optic elements initially. This function could ultimately be accomplished by a simple transmission hologram element. The image source consists of collimated light modulated by a reflective liquid crystal flat matrix display. The light source is an efficient Thallium arc

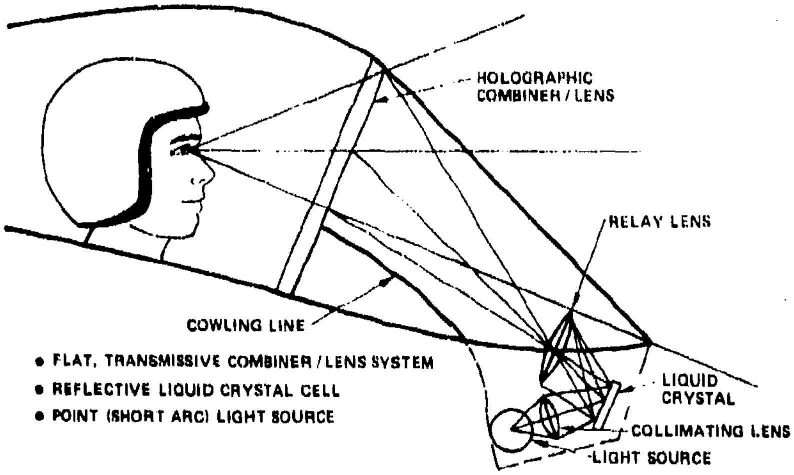


Figure 1-1. Advanced HUD baseline configuration.

source which emits a narrow band of light at the wavelength required by the holographic lens. The liquid crystal display is addressed in a TV raster scan format and thus is compatible with most sensor and symbol display requirements.

This design provides several important advantages over head-up displays that use conventional optics and image sources; they are:

- Higher brightness than with CRTs
- The holographic combiner provides wider field of view than can be obtained with conventional optics.
- Narrow spectral response, intrinsic to hologram optics, results in an image combiner that is free from coloration; thus, the outside view appears as it normally would through conventional windscreens without tinting.
- High diffraction efficiency of the hologram phase recording preserves high brightness while reducing the power required for internal illumination.

The performance parameters of the baseline system are shown in detail in Table I-1. These were derived during a design study aimed at meeting the following goals:

• Field-of-view	60 degrees Horizontal x 45 degrees Vertical
• Resolution and accuracy	1 mrad over full instantaneous field-of-view

TABLE I-1. ADVANCED HEAD-UP DISPLAY SPECIFICATION

Field of view	60 degrees horizontal by 45 degrees vertical
Brightness	Provides 1.8 contrast ratio with 10K fL background (8K fL)
Transmission	90 percent (no tinting of outside scene)
Color	Narrow band centered at approximately 5350 Å
Accuracy	25 mrad over entire FOV (presently, will improve with further development of continuous lens
Resolution	Total 768 x 1024 elements (approximately 1 mrad)
Size	Combiner 21 x 28 inches outside dimensions (1/4 inch thick) Projection Source: 15" x 8"x 10"
Weight (total)	25 pounds
Power	200w
MTBF	2000 hours (Recommend lamp replacement at 1000 hours)
Functional capabilities	Daytime Sensor Display with gray shade rendition
	Growth potential to provide color. TV compatible display format

•	Brightness/Contrast	Adequate for good visibility of symbology against a 10K fL background brightness
•	Functional capability	Symbology
		Pictorial sensor information
		Growth to color
•	Physical characteristics	Minimum weight, power, volume, and impact on forward vision

It is noted that the only parameters presently not meeting these goals are resolution and accuracy. The 25 mrad accuracy resulted from a limited computer analysis of a specific holographic lens matrix. It is known that the accuracy can be significantly improved by a more extensive design effort which would have been beyond the scope of this program. In this regard, recent developments at the Hughes Malibu Research Laboratories on a company-sponsored IR&D program have revealed that hologram lens performance can be considerably improved by generating a "continuous lens" which approximates the performance of a lens array containing an infinite number of array elements.

To fully carry out a design of this type requires the use of existing large scale computer programs which, after modification, would be able to perform off-axis ray traces and an assessment of image quality throughout the entire visual angle. The modification of these programs and the systems design of hologram and projection lens components would be the next logical step in the continuing development of the advanced HUD.

The fabrication techniques for the continuous hologram lens are known and sample lenses of high quality have been constructed by processes which could be used for the baseline design.

In the course of the study, several alternate configurations were investigated. These designs are more applicable for long range development. One such alternate is to provide the holographic lens/combiner function integral with the canopy. This is very desirable since it essentially provides the full forward field of view. It does, however, require a more complex curved lens array. Also, the projection requirements are more difficult. Another alternate is to use a transmissive liquid crystal matrix display illuminated by a diffuse, panel light source. The major advantage for this method is simple overall optical design that results. These alternates are, however, further downstream in terms of development time. The baseline as shown could conceivable be developed to provide a flight test system in 1976.

1.4 Design Feasibility

In comparing the estimated performance with the design requirements, the only parameter which does not appear to be realizable at this time is the accuracy of 1 mrad over the entire 45 x 60 degree field of view. Improvement in holographic optics design techniques presently underway at Hughes Malibu Research Laboratories and inclusion of electronic compensation should ultimately provide this accuracy.

To refine the design goals and to obtain further insight into the actual use of HUDS, a user survey was conducted. Experienced A-7D pilots were interviewed and their remarks with regard to an improved head-up display were tabulated. The results of the interview are presented in Appendix B.

In addition to the study effort itself, two deliverable demonstration items were developed. The first utilizes a simple single element holographic lens in conjunction with a reflective display and light projector to indicate the operation of the holographic optical element as a combiner and lens. Also, a half-scale mockup of a typical cockpit installation was built. These devices are discussed in Appendix A.

In conclusion, it can be stated that the development of an advanced head-up display employing a holographic lens/combiner and liquid crystal display source is feasible. It appears that such a display will provide a marked improvement in the performance (FOV, brightness) over existing head-up displays. This improvement is accomplished while maintaining small size, light weight, low power, and high reliability due to the solid state nature of the display and reduction of optical complexity.

2.0 REQUIREMENTS ANALYSES

The head-up display (HUD) provides the pilot a partially transparent collimated image of various symbols and sensor video. Thus there is "see-through and everything is at infinity. The symbols and video are selectively displayed and are used for flight control, weapon delivery, and navigation. The desired performance characteristics of a HUD may be derived from an analysis of the information required for each mode of operation, from the visual demands of the pilot, and from the tactics, weapons, and flight envelope of the aircraft. From these factors the actual design parameters of brightness, resolution and field of view can be derived. It is these parameters (or design goals) that are the basis upon which the actual design is conducted.

The starting point for the requirements analysis was the assumption of boundary conditions. These included the aircraft type, the weapon complement, the sensor complement, and a sample of representative missions. These working assumptions are listed in Table II-1.

2.1 Information Requirements

The information requirements were derived by developing detailed operational sequence diagrams for the critical modes of air-to-ground weapon delivery, air-to-air attack, and approach and landing. A summary of the results is shown in Table II-2. To visualize the appearance of the display and assess the amount of symbol clutter, representative symbols to provide the required information were taken from MIL-D-81641 (General HUD Specification) for what was considered a worst case situation. These are shown in Figures 2-1 through 2-3. Visual clutter can be alleviated by

TABLE II-1. BASELINE SYSTEM ASSUMPTIONS

Aircraft	Weapons	Sensors	Mission Phases
Attack (A-7)	TV missile	Multi-mode radar	Take-off
	FLIR missile	Television	Departure
	Anti-radiation missile	FLIR	Enroute navigation
	Guns, fixed	Laser ranger	Air combat
	Guns, trainable	Laser illuminator	Air-to-ground weapon delivery
	Rockets	Laser receiver	Rendezvous
	Gravity bombs	Radar homing	Station keeping
	Air-to-air missile	IR surveillance	Inflight refueling
		NAVAIDS	Terrain following and avoidance
			Approach and landing

TABLE II-2. HUD INFORMATION REQUIREMENTS BY MISSION PHASE

	Air-to-Ground Weapon Delivery	Air-to-Air		Approach and Landing
		Missile	Gun	
Pitch and roll	1	2	2	1
Cmd pitch				
Airspeed	2	2		1
Altitude	2			1
Cmd altitude				2
G's		2		
Angle of attack				(option)
Localizer				1
Glide slope				1
Flight path marker	1			1
Runway symbol				2
Standby reticle	1	1		
Mode discretes	2			2
Steering	1			1
Designation cursor	1	1		
CCIP	1 (option)			
Bomb fall line	1			
Solution cues	1			
Pull up cue	1			
Breakaway	1			
IN range	1			
Range	2	2	1	1
Time to go	2			
Heading				1
Cmd Hdg				2
Lock on signal		1		
Firing envelope		1		
Maximum range		1		
Minimum range		1		
Hot line			1	
Radar line of sight		1	1	
Vertical speed				1
Television	2			2
Forward looking infrared	2			2
Radio frequency	1	1		1

1 Recommended

2 Desireable

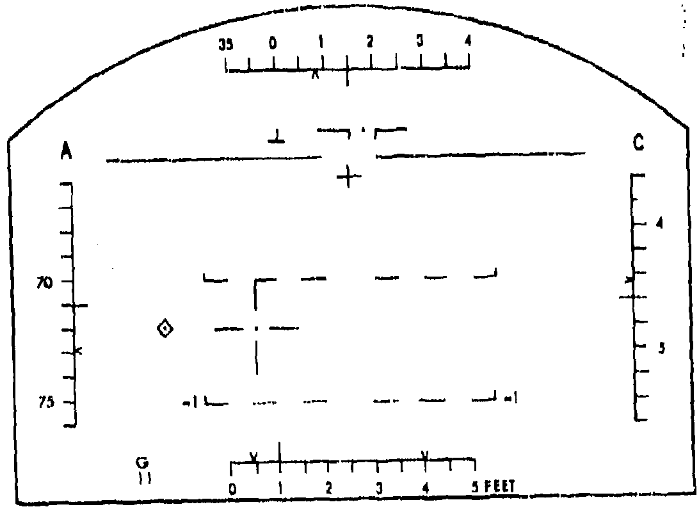


Figure 2-1. Boresight weapon mode.

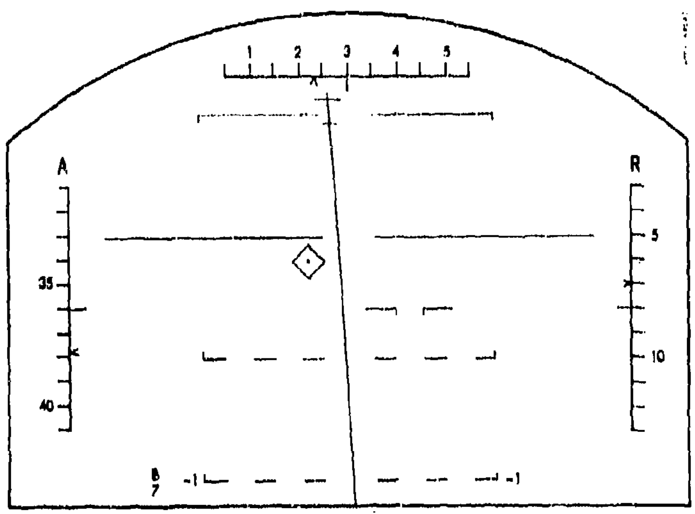


Figure 2-2. Bombing mode.

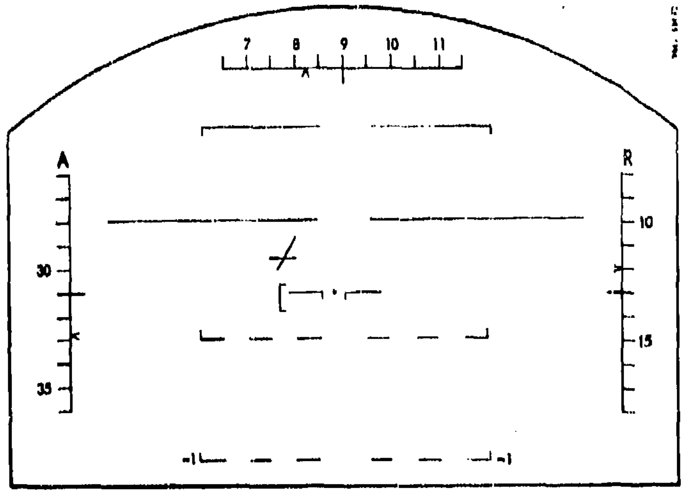


Figure 2-3. Landing mode.

increasing the display size (field of view), and these samples illustrate the clutter possible on a HUD as well as examples of the complexity and size of the symbols required.

2.2 Sensor Display Requirements

In the A-7, current plans call for HUD display of FLIR sensor video. The FLIR is used for finding targets, and the sensor is slewable with a variable field of view. The widest sensor field of view is on the order of 5 x 7 degrees, while the HUD display has a field of view of approximately 15 degrees. This combination of characteristics means that the video will never be in registry with the outside world. Nevertheless, pilots that have flown test versions of the system found it useful at dusk and at night.

To develop future requirements for HUD display of sensor video based on formal analyses was beyond the scope of this program. However, assumptions were made to develop a first cut at the requirements.

In an attack aircraft the sensor data will be used primarily for weapon delivery. To increase recognition range and designation accuracy, emphasis is placed on system resolution rather than sensor field of view. At unit magnification, the pilot's eye is better in resolution than the sensor-display

combination. Therefore to improve the ability of the pilot to resolve objects on the ground, the sensor field of view is kept narrow but magnified on the display; for example, 10 degrees of sensor data is spread over 30 degrees of display. Until marked improvements in sensors take place, the field of view of the display will be larger than the sensor field of view. Magnification may vary from 1:1 to 10:1. It is not likely, then, that registration of sensor imagery with the outside world will take place in the near future. This implies that the dynamics of the sensor imagery will be different than the dynamics of the directly seen visual world.

As sensor technology grows, both the resolution and field of view will grow larger. It is important that displays be developed to accommodate these future systems. Sensors with a capacity of 1000 picture elements per axis are not out of the question. To reproduce a 1000 elements, a display matched to the eye would require a field of view of about 17 degrees.

To provide a headup sensor display for flight control or terrain following requires correct image dynamics and a wide field of view. Hence the HUD must provide unit magnification and wide field of view. Studies by Bell Helicopter have shown that a horizontal field of view approaching 60 degrees is required to provide the flight control function.

Also it is not considered desirable to limit the presentation of sensor video on the HUD to strictly night time conditions (as with the A-7). The ability to provide sensor video head up during the day time is considered necessary in an advanced HUD. Low level ground fog penetrated by an advanced E-O sensor is one example. In such a case a bright HUD is required due to the bright background. As more advanced sensors become available they will undoubtedly be used under most conditions both day and night. Samples of typical television and forward looking infrared video that could be displayed on the HUD are shown in Figures 2-4 and 2-5.

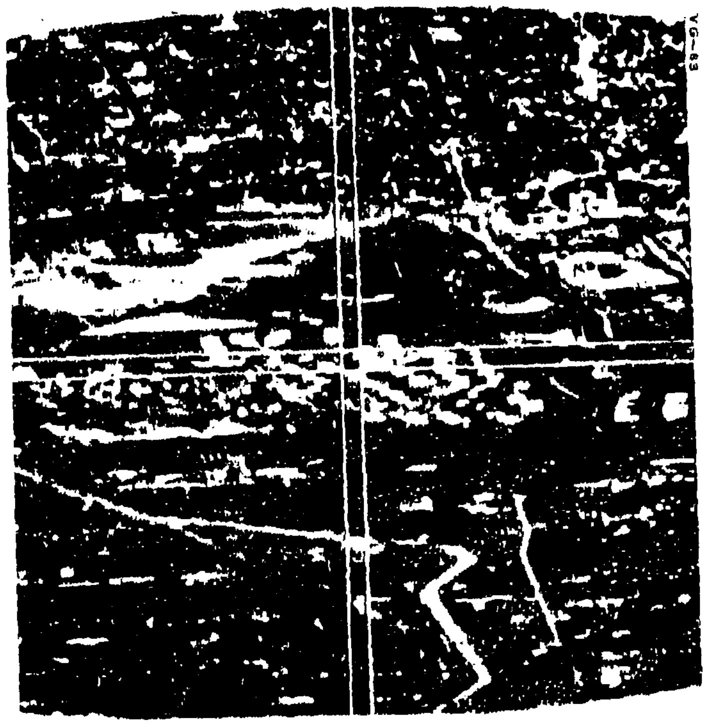


Figure 2-4. HUD TV format.

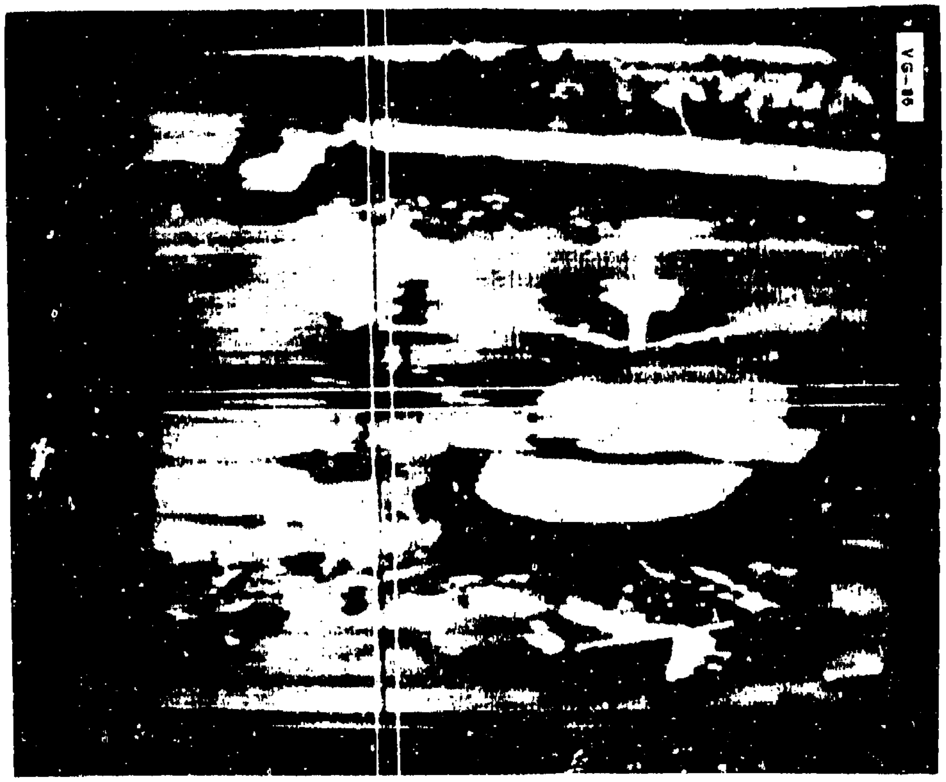


Figure 2-5. HUD FLIR format.

2.3 Brightness, Contrast, and Resolution

The symbols and sensor video displayed must be visible, legible, flicker free, and stable. To meet these criteria, the HUD must be designed to match the visual demands of the pilot in the operational environment. Visibility is determined primarily by contrast and brightness; legibility by symbol size, contrast, and system resolution; flicker by the refresh rate; and stability by symbol jitter. The quality of the video image will be mainly a function of the image dynamic range and system resolution.

The contrast between the symbols and the sky background must be sufficient if the symbols are to be visible. Contrast ratio is defined as B_1/B_2 where B_1 is the symbol image brightness and B_2 is the sky brightness as viewed through the HUD. As the symbols are comprised of lines whose width is approximately 1 milliradian (per MIL-D-81641), the required contrast ratio is about 1.8. An extreme sky brightness is 10,000 foot lamberts.

Ignoring the light loss through the HUD combiner, the minimum required brightness of the symbol images is approximately 18,000 foot lamberts. As the sky accounts for 10,000 foot lamberts, the additive brightness is 8,000 foot lamberts. The above criterion contrast ratio is conservative; that is, one is assured that symbols that meet this criterion will be readily visible. This contrast requirement coupled with the background brightness of 10,000 fL imposes severe brightness requirements on the display device. A design that meets these requirements will assure that the symbols can be seen in all but the most severe ambients.

The quality of the display of sensor video in the HUD is dependent on the gray shade rendition. The number of gray levels may be estimated if one assumes that a gray level constitutes a change in luminance by a factor of $\sqrt{2}$. For example, a brightness dynamic range of 4 to 1 provides 4 shades of gray ($\sqrt{2}^4 = 4$). Assuming a combiner with 80 percent transmission, and a maximum brightness capability of 8000 fL., Table II-3 shows the number of shades of gray provided as a function of the ambient brightness level.

TABLE II-3. EFFECTIVE DYNAMIC RANGE, AND NUMBER OF GRAY SHADES AS A FUNCTION OF AMBIENT ILLUMINATION

(For a HUD with 80 percent transmittance)

(assume $\sqrt{2}$ gray shade steps)

Ambient Illumination $I_a = 0.8 \times$ (outside, fL)	Image Luminance i_0 (in zero ambient, fL)	Additive Image Brightness $I_a + I_0$ (fL)	$R_e = \frac{I_a + I_0}{I_a}$ (effective dynamic range)	Gray Shades $= \log_{\sqrt{2}} R_e$
8,000 (10,000)	8,000	16,000	2.0	>2
4,000 (5,000)	8,000	12,000	3.0	>4
1,600 (2,000)	8,000	9,600	6.0	>6
800 (1,000)	8,000	8,800	11.0	8

From examination of this table one can conclude that at extremely bright ambients (10,000 FTL), which approximates snow or white clouds in sunlight, it will be difficult to see anything but the symbols. At more moderate ambients (2000 FTL), which approximates average sky and earth brightness, the display whose highlight luminance is 8000 fL will reproduce in excess of six shades of gray. On dull days and at dusk, a high luminance display will provide a full gray scale.

The visibility of HUD symbols depends on brightness and contrast, however the legibility of the alphanumeric characters depends on symbol size, stroke width, and system resolution. Figure 2-6 illustrates the interaction between alphanumeric symbol size and resolution with a criterion curve drawn at the loci where the alphanumerics will be correctly identified 95 percent of the time. This criterion curve was derived from laboratory data for high contrast symbols. Alphanumeric legibility is also a function of the ratio of stroke width to symbol height. Acceptable ratios are on the

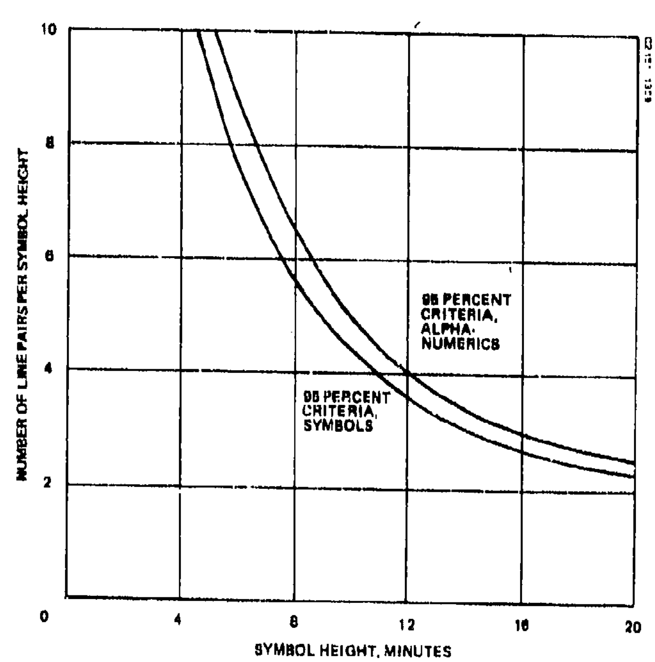


Figure 2-6. Criteria for alphanumerics and symbols.

order of 1:10. If the stroke width is 1 milliradian, the required symbol height is 10 milliradians; i.e., 30 arc minutes, which easily meets the size requirements for legibility. A stroke width of 1 milliradian implies a system resolution of 0.5 line pair per milliradian which would mean 5 line pairs per symbol height, thus meeting the symbol resolution requirement. One milliradian is also the resolution specified by MIL-D-81641. This specification is summarized in Table III-1 in the next section of this report.

2.4 Flicker

The required field rate for a flicker free image is derived solely from the characteristics of the eye. Figure 2-7 shows a characteristic curve of critical flicker frequency (CFF) for a range of brightnesses. These data were gathered in the laboratory where the typical experimental conditions were whole field, square wave, brightness fluctuations. Examination of this curve indicates that a 60 cycle field rate will provide a flicker free image.

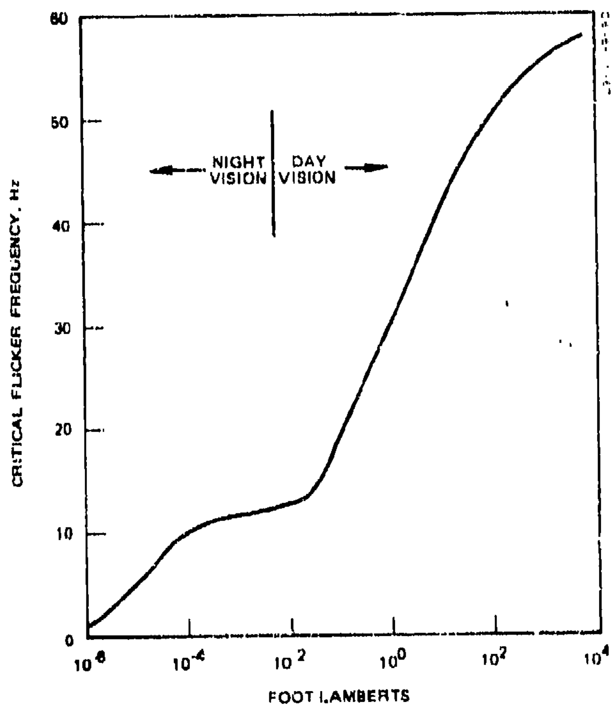


Figure 2-7. Critical flicker frequency.

2.5 Field of View

Present optical designs limit the monocular instantaneous HUD field of view to approximately 15 degrees. Consequently, too much symbolic information can be presented in this small area, resulting in an objectionable cluttered display. The next generation HUD designs should simultaneously fulfill the needs for sensor displays, flight envelopes of the aircraft, weapon delivery requirements, and symbol clutter alleviation. Ideally, the HUD display should utilize the entire windscreen field of view.

Field of view requirements derived from television or FLIR sensors are a function of the sensor field of view, the display magnification, the sensor resolution, and the HUD resolution. Airborne video sensors characteristically have multiple fields of view, but seldom does the maximum field of view exceed 20 degrees at this time. If a 1:1 relationship with the outside world is required, a HUD field of view of 20 degrees is needed. It is anticipated that sensor (e.g., FLIR) fields of view will increase in the future and a 60 degree field of view is not at all unrealistic for the next decade.

One of the most useful pieces of information presented on a HUD is the flight path angle of the aircraft. The symbol representing this information shows the pilot where the aircraft is going in inertial space. Pilots who have flown HUDs are universely enthusiastic about the presentation of this quantity. This means that at a minimum, the field of view of the HUD should be large enough to portray the flight path angle (FPA) in real space.

In the horizontal axis, the position of the FPA indicates crab angle. The most severe and critical crab angles occur during approach and landing. For conventional attack aircraft, landings may be executed with cross winds up to 20 knots at airspeeds as low as 120 knots. This means a displacement of the FPA of ±10 degrees. Allowing for emergencies that may exceed these limits and to insure that the FPA is not at the extreme limits of the display, a horizontal field of view of ±15 degrees is recommended.

The vertical field of view, based on the operating envelope of the aircraft, may be derived primarily from the angle of attack limitation of the

aircraft, coupled with a headwind during approach and landing. In the extreme case, the typical conventional attack aircraft can land with angles of attack approaching -30 degrees. With a headwind, the FPA will exceed -30 degrees. However, the over the nose vision rarely exceeds 22 degrees. As the utility of the HUD flight symbols is greatly reduced when they cannot be seen in the context of the outside world, the HUD field of view in the negative vertical dimension can be limited to the over the nose envelope. Requirements for the positive vertical field of view, that is, above the fuselage reference line, cannot rationally be derived from the flight envelope of the aircraft. The most that can be said is that there may be a desire for a certain degree of symmetry and a need to have a field of view large enough to accommodate symbology without clutter. Therefore +22 degrees should suffice.

For an attack aircraft, the HUD field of view dictated by weapon delivery requirements is primarily dependent on the lead angle of fixed guns, the trail of gravity bombs, and the off-axis requirements of trainable guns should they be carried. In air combat with fixed guns, lead angles seldom exceed -8 degrees in elevation, a few degrees in azimuth, and occasionally +4 degrees in elevation. The trail of gravity bombs varies considerably; for high drag bombs dropped in relatively shallow dives, the trail can exceed -22 degrees — the limit for over the nose vision. For trainable guns, Hughes analysis have shown that at off-boresight angles greater than 30 degrees the tracking equations become so complex as to preclude the possibility of accurate aiming. A summary of the field of view requirements based on these considerations is provided in Table II-4. It can be concluded from this table that a horizontal field of view of ±30 degrees should be provided in an advanced HUD. A vertical field of view of ±22 degrees was selected to maintain a 3:4 aspect ratio and meet all requirements in the table.

2.6 Summary of Head-Up Display User Survey

During the contract period a Head-Up Display User Survey was performed to obtain HUD design requirements data from the user's (pilot's) standpoint and to take advantage of the operational experience gained by pilots

TABLE II-4. HUD FIELD OF VIEW REQUIREMENTS

Source of Requirement	Azimuth	Elevation
Landing	±15 degrees	+5 degrees, -22 degrees (over the nose) (A-10 aircraft)
Trainable guns	±30 degrees	–
Fixed guns	±5 degrees	+4 degrees, -8 degrees
Bombs	±10 degrees	-22 degrees (over the nose)
Sensor video	±10 to 15 degrees present ±30 degrees future	±10 degrees ±15 degrees future
Flight control	±30 degrees	

using a HUD. Since the A-7 was initially selected as the representative aircraft system in which the Hughes HUD requirements were conceptually examined, it was decided to concentrate the survey efforts on pilots experienced in that aircraft. In all, 17 highly experienced pilots were administered the survey. The estimated average total flying time of these pilots was 2,216 hours (330 to 4100 hours). Their average total A-7 HUD time was 284 hours (75 to 800 hours). The questionnaire and summary of pilots response is provided in Appendix B. Based on the user survey, the following conclusions and observations can be made.

1. The A-7D HUD is a superior head-up pilot instrument. It is highly functional for most mission segments in which it is used. It is universally accepted by the pilots surveyed. It does have some limitations which should be avoided in future HUD designs. Those limitations which may have the greatest impact on the Hughes design concepts are identified below.

2. Brightness and contrast problems experienced during night operations were identified by 10 out of 17 pilots. On subsequent questioning, it was learned that brightness/contrast problems

were experienced by all the pilots to some degree at night, though some felt the problems to be insignificant. The greatest problem was expressed in reduced target visibility when viewed against a background of lights (city lights, flares, and stars), or when the target was imbedded in the lights.

3. With respect to the above, the adequacy of automatic brightness control of the HUD was expressed in the survey. Some pilots felt that the control was fine as it is. Others said that it is good, but that they would like to have manual override capability to exceed both the upper and lower limits of the automatic brightness control feature. They felt this would help mainly during the target acquisition and attack sequence.

4. Several pilots indicated the symbology was washed-out when flying toward the sun. One can also expect such a problem to a lesser degree from bright cloud reflections. The brightness/contrast recommended should eliminate this problem.

   It is stressed however that, all the pilots agreed that the A-7D HUD symbology is readable during most night and day conditions. These pilots were not questioned on the presentation of sensor video on the HUD since it is not operational as yet. The A-7 HUD is not sufficiently bright to display sensor video during the day.

5. Several pilots expressed concern about symbology drifting off the display (i.e., Flight Path Marker, steering dot, etc.). They do not want the symbol to disappear but to perch at the edge of the HUD. It was suggested, for example, that the steering dot should not be permitted to drift off the display. Instead, as the horizontal HUD FOV limit is reached the symbol should freeze at that point in azimuth, but be permitted to move upward and downward at the azimuth limit. With this information, the pilots believed they could continue flying the symbol of interest for its predictive value and fly the steering dot back into the HUD FOV. A larger field of view will alleviate this problem.

6. Another problem was the effect of too much symbology during critical operations, particularly during strafing. Symbology tends to collect in a clump around the target, often hiding it from the pilot's view. The consensus was that the HUD be provided with an automatic feature to limit symbology to only that which is required at any instant in time during periods of critical performance. A larger field of view HUD will allow more spacing between symbols thereby reducing this clutter.

7. Pilots generally favored using the normal green symbology during night operations when discriminating target or objects of interest against a lighted background (city lights, stars,

flares, etc.), rather than using other colored filters. They reported that lights viewed through the HUD combining glass appeared orangish. The use of green symbology seemed to offer the best contrast technique for minimizing the effects of symbology washout due to background lighting. A requirement for an advanced head up display is to provide green symbology.

8. There were only a few direct responses to the question concerning FOV. Of those that did respond, all thought that a wider horizontal FOV would be desirable. None thought that a greater vertical FOV would add capability (it should be noted that these pilots mainly fly air-to-ground missions and seldom air-to-air combat).

   When asked, "What is your choice for a HUD vertical field of view point of reference relative to the longitudinal axis of the aircraft?", the consensus strongly favored the velocity vector (flight path marker on the A-7D HUD). The predominant reason given was that they want to know where the aircraft is going, not where it is pointed.

9. A response shared by several pilots (and generally concurred with by the other pilots on direct questioning) was the desire for display of the selected radio frequency and an alternate radio frequency on the HUD. According to the pilots, unless there is good radio contact between the element leader and his wingmen, and between the element leader and external command and control (e.g., FAC), there is little chance for concluding a successful attack on a selected target. This is particularly the case in close air support missions, where positive target identification and confirmation is a must requirement before the weapon can be committed. Experience indicates that it is not uncommon for the UHF channel to become unreliable at critical times. Pilots would like to be able to see what the primary and alternate frequencies are so that they may quickly make the new selection. Of course, to include more information on the HUD does contradict the previously stated cluttered display objection. With a larger field of view however, the information is less crowded.

2.7 Conclusions

Based on the quantitative analyses and qualitative considerations in this section, the requirements, or "Design Goals" of an advanced head up display are summarized in Table II-5.

TABLE II-5. ADVANCED HEAD-UP DISPLAY DESIGN GOALS

Field of View	
Horizontal	±30 degrees
Vertical	±22 degrees
Brightness/Contrast	Provide contrast ratio of 1.8 with 10K fL ambient
Transmission	Maximize
Resolution/Accuracy	Maintain 1 mrad over entire field of view
Refresh Rate	60 hz minimum
Color	Green

3.0 EXISTING TECHNOLOGY AND AN ADVANCED HUD CONCEPT

3.1 Introduction

In this section, state of the art head-up displays are discussed. The techniques employed in conventional designs are presented, and their limitations with regard to their ability to meet the advanced HUD design goals are discussed. A tradeoff table of operational systems is also presented. The basic types of existing HUDs can be characterized as electromechanical or CRT source systems with reflective or refractive optics. These types of HUDs are discussed along with the concept of an advanced HUD. The advanced HUD concept consists of a holographic combiner and a liquid crystal modulated light source to provide a bright, wide field of view system.

3.2 Existing HUDs

3.2.1 Electromechanical Head-Up Display

Electromechanical head-up displays are mainly analog devices using synchros and meter movements for symbol positioning. This approach has had extensive operational use in lead-computing optical sights. The symbols are deflected throughout the field of view by means of servomechanisms acting on components in the optical path. A color display is achieved by inserting a filter in the optical path. Figure 3-1 illustrates a typical electromechanical design.

The electromechanical head-up display exhibits disadvantages common to electromechanical servo systems such as hysteresis and limited dynamic response. In addition the electromechanical HUD has very little growth potential. The head-up display interfaces with the central digital computer.

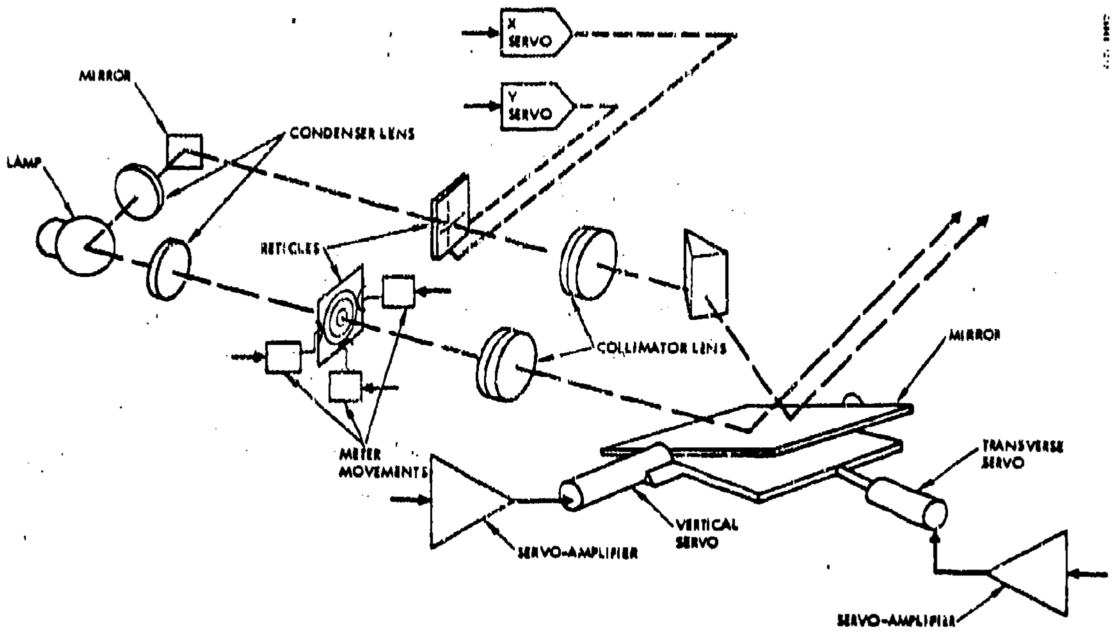


Figure 3-1. Electromechanical HUD.

Since the electromechanical head-up display is an analog device, complex digital-to-analog converters are required for the interface. Other disadvantages are the excessive weight of the mechanical components and the low reliability of motors and solenoids. This low reliability provides a symbol positioning accuracies within ±1 milliradian are possible. The overall display quality of an electromechanical head-up display, as demonstrated by one vendor, is excellent. The symbology presented is bright, sharp, noise-free, and in vivid color.

3.2.2 Cathode-Ray Tube Head-Up Display

In a CRT head-up display, a high resolution, high brightness tube is utilized for all symbol writing. The sumbols are projected on a combining glass with an optical system. The symbols are positioned by deflecting the CRT electron beam rather than using servomechanisms as in the case of the electromechanical head-up display. This approach offers instantaneous symbol response, simultaneous presentation of a large number of symbols, and

growth potential. Removal of information is accomplished by blanking the CRT. The display quality is limited by the CRT resolution and brightness. As in any cathode-ray tube display, the method is susceptible to electromagnetic and electrical noise, and the system is sensitive to its operational environment. The HUD must be boresighted to the aircraft line of sight and is therefore hard-mounted, which subjects it to a higher level of shock and vibration. Therefore, the CRT must be extremely rugged to withstand this environment. The imaging from the CRT is collimated and displayed by either a refractive or reflective optical system.

Refractive Optics

In refractive optics, a refracting lens is used for image collimation, and a flat, partially reflecting, transparent mirror combines the images with the real-world view as illustrated in Figure 3-2.

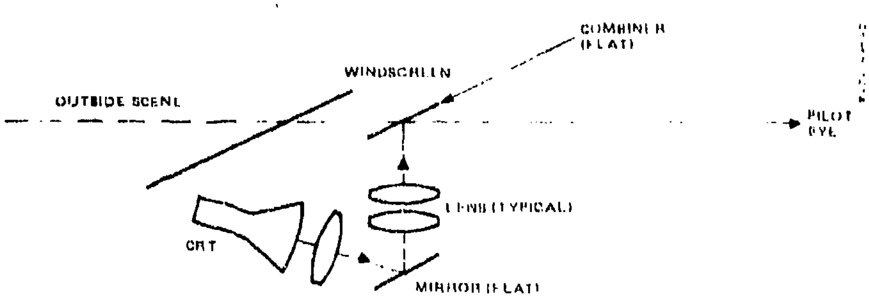


Figure 3-2. Refractive system.

The instantaneous monocular field of view is limited by the lens diameter and the eye-to-lens distance expressed by the following equation:

$$\alpha = 2 \arctan \frac{\text{lens diameter}}{2\,(\text{eye-to-lens distance})},$$

where

α = total angle subtended by the pilot's eye.

Binocular field of view represents the superposition of the instantaneous fields as seen by each of the observer's eyes. The instantaneous horizontal binocular field of view is expressed as

$$\alpha = 2 \arctan \frac{\text{lens diameter} + \text{eye spacing}}{2(\text{viewing distance})}.$$

It is apparent from the foregoing equation that the instantaneous field of view is proportional to the lens diameter. Increasing the lens diameter requires a proportional increase in the size of the reflecting mirror and consequently an increase in the required front panel area.

Limited head motion will result in varying portions of the display being visible, i. e., the exit pupil of the optics is some finite distance in front of the pilot, thereby appearing to the pilot as a knothole through which he must look. The total field of view, that which is obtained with head movement, is a function of the real object (CRT) diameter and the effective focal length of the lens system defined by the relationship:

$$\alpha = \arctan \frac{\text{CRT diameter}}{\text{focal length}}.$$

A short focal length is desirable for a system with a large total field of view in order to keep the CRT size, optical path, and hence package size to a minimum. Since a CRT has an appreciable line width, a short focal length will have an adverse effect on the display resolution and is undesirable from this standpoint. The line width perceived by the pilot is expressed by the following equation:

$$\theta = \frac{t}{F} \text{ radians,}$$

where

θ = angular aperture of t projected to infinity

t = CRT line thickness

F = focal length

Reflective Optics

In off-axis reflective optics as illustrated in Figure 3-3, the image source and observer's eye are off-axis with respect to the optical axis of the aspheric mirror and combiner. The effect of this displacement is that the optical design is made difficult. The system must handle rays that are significantly inclined to the axis and those rays must be accurate in order to minimize magnification distortion. As a result, the large reflecting surface of the combiner lens and one or more other lens surfaces must be aspheric. This approach then permits a real exit pupil to be projected just forward of the pilot's eye.

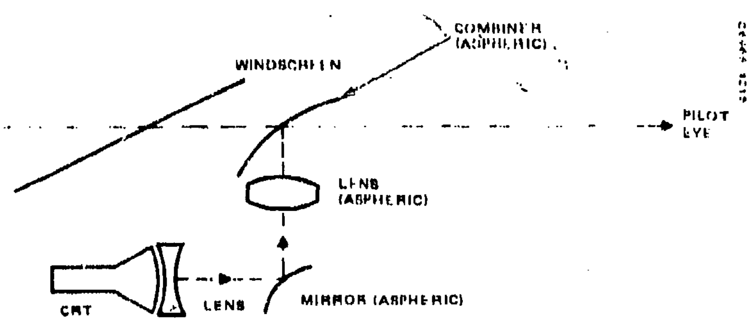


Figure 3-3. Off-Axis (folded) reflective system.

The forward surface of the aspheric combiner must be designed to minimize the distortion of the outside world. This is extremely difficult to accomplish, since the distortion is a complex function of eye position. The field of view limiting element of the off-axis optics is the size of the combining glass.

The on-axis optics shown in Figure 3-4 effectively puts the image source, reflective optics and observer's eye on the same optical path. The combining glass acts as a double beam-splitter since the CRT light must pass through it before collimation. This results in a lower optical efficiency. The collimating element in the on-axis optics is a spherical mirror which can be manufactured accurately and efficiently. The size of the spherical mirror is the field of view limiting element. This design requires that the CRT have a spherical face. The one objection to this design is the fact that

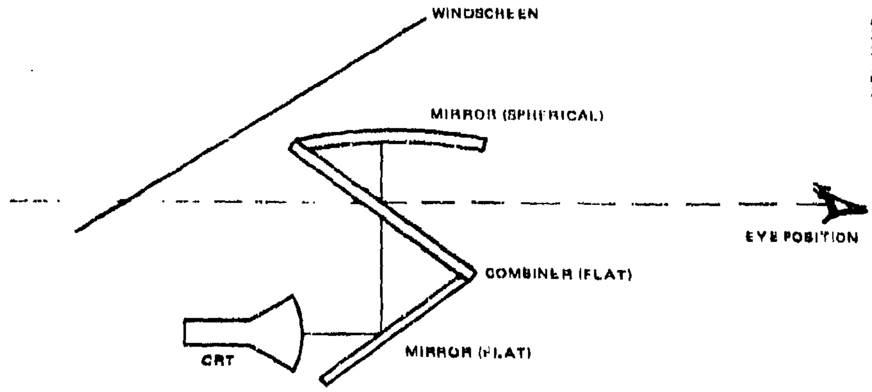


Figure 3-4. On-Axis reflective (folded).

the overhead spherical mirror obscures approximately one degree of vertical field of view. This one degree is, however, above the field of view of the HUD.

3.3 Limitations of Existing Technology

Head up displays employing existing techniques are limited in their performance due to the capabilities of conventional optics and CRTs. A tradeoff summary of several state-of-the-art HUDs, and HUDs in development are compared in Table III-1, along with the design goals of the Hughes advanced HUD. It is seen that existing HUDs do not meet these goals. Their limitations with regard to major performance parameters, namely, field of view, brightness, and accuracy are discussed below.

3.3.1 Field of View

The optical design for state-of-the-art HUD optics systems has been well established for some time, and a number of systems have been designed for a 20-degree field of view using flat and spherical combining surfaces. For wider fields of view in conventional HUD systems, the optics become very large, and in general field flattening and distortion compensations become overpowering design constraints. This means that for the larger systems, such as a 30-degree field of view or larger, the combining optics will generally be aspheric because of the wide angles, the large lens

TABLE III-1. HEAD UP DISPLAY TRADEOFF SUMMARY

Parameters	A-7E Elliott	F-111D Norden	F-14A Kaiser	F-15 McDonald/ Douglas	Wide Angle HUD Farrand	A-4M Elliott	Hughes Advanced HUD Design Goals	MIL SPEC MIL D 81641 (AS)
Type	CRT/Refractive optics	CRT/Reflective optics	CRT/Refractive optics	CRT/Refractive	CRT/Reflective	CRT/Refractive	Advanced Techniques	NA
Field of View instantaneous (V x H)	$10.8^\circ \times 16.1^\circ$: $11.2^\circ \times 16.4^\circ$ (Binocular)	$14^\circ \times 16^\circ$ (Binocular)	$14.1 \times 18.2^\circ$ (Binocular)	$12^\circ \times 17^\circ$ (Binocular				$20^\circ \times 28^\circ$
Total (V x H)	$20^\circ \times 20^\circ$	$20^\circ \times 20^\circ$	$20^\circ \times 20^\circ$	$20^\circ \times 20^\circ$	$35^\circ \times 25^\circ$	$11^\circ \times 16^\circ$	$45^\circ \times 60^\circ$	
Viewing Distance, in.	29	25	22	33	15	20°		
Display Accuracies	1.1 mr in center 10° 1.6 mr within 10° to 20°	NA	NA	1.5 mr in center 3° 3.0 mr within 3° to 20°	2 mr	1 mrad center 3 mr edge	1 mrad over FOV	1 mrad (central 12°)
Brightness (max), fL	1500	1500	1600	1500	1500	1000 F+L	Full resolution symbols in 10K fL ambient 1.8 contrast ratio	–
Combining Glass Transmissibility, %	75	73	70	75	NA	85	Maximize	80
Weight, lbs	6-	23	53	55	25	13	Minimize	<70
Power, watts	230 W	100	375 VA	NA	NA	80 W	Minimize	<300w
Volume, ft^3	1.5	0.45	1.55	1.1	0.31	0.4	Minimize	1.8
Cockpit Front Panel Space	4-1/2" x 5"	5" x 6-1/2"	NA	8" x 11"	5" x 6"	4-1/2 x 5"	Minimize	–
MTBF, hours	1007	NA	214 (combined HUD/VSO)			1000 hrs	Maximize	1000 (500 hrs CRT)

diameters, and the short focal distances involved. The requirement to use aspheric optics is based on the use of the additional magnification surfaces allowed by the aspheric mirrors, even though aspheric optics are undesirable due to the specialized, expensive fabrication techniques required. One desirable feature of an optimum head-up display is to provide the combiner function integral with the aircraft canopy. The use of a classical projection system to achieve this goal is considered a formidable, if not an impossible task.

A wide angle Farrand head-up display is under development which comes close to meeting the field of view design goals. This system, shown in Figure 3-5, utilizes complex aspheric reflective optics with a CRT to project the presentation on a curved combiner. In order to keep the combiner small, it is placed close to the user's eye (15 inches). This requires the placement of a mirror very close to the viewer's face. Unfortunately, this mirror is within the ejection envelope and must be folded out of the way upon ejection from the aircraft. It is estimated that a very complex lens system with greater than 10 optical elements is used in this HUD. Also, in order to circumvent the ejection envelope interference problem with the Farrand HUD, a larger combiner must be placed farther away from the viewer. This necessitates the use of an extremely large exit lens diameter.

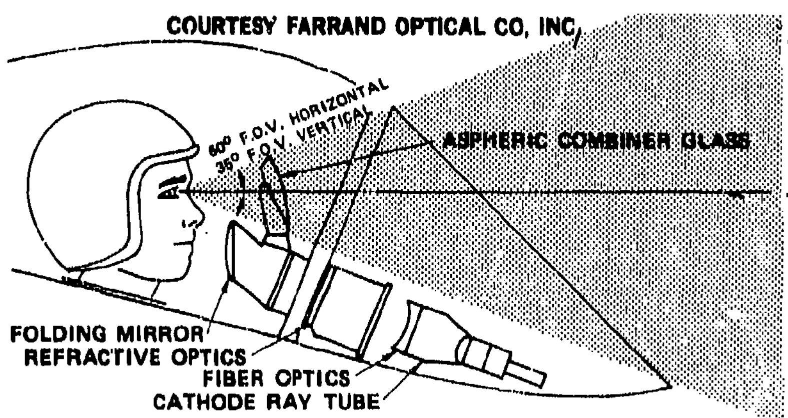


Figure 3-5. Farrand wide field of view head up display.

3.3.2 Brightness/Contrast

The ability to see symbology or video on a HUD with a bright background ambient is determined by the contrast of the presented video with respect to the background. The design goal for the HUD is to provide a contrast ratio of 1.8 against a 10,000 foot lambert background (solar reflection from white cloud). There are several parameters which effect the ability of a HUD to meet this requirement. One is the brightness of the source (CRT or a projection lamp modulated in some way to provide the symbology); another is the efficiency of the optical system. The optical efficiency is defined as the ratio of the output brightness to the input brightness. Assuming all lenses are anti-reflection coated, the surface reflections and bulk absorption should be lower than 2 percent, and the mirror used in a reflective optics system can be 95 percent reflective. Hence, these components are not considered to be the major factor which determines the optical efficiency of the conventional HUD. The major factor is that of the reflectivity and transmission of the combining glass. Assuming a simple broad band combiner with 50 percent transmission and 50 percent reflectivity, the 10,000 foot lambert outside ambient is reduced to an apparent 5,000 foot lambert background. Since a 1.8 contrast ratio is needed, an apparent 8,000 foot lambert image source is required since only 50 percent of the source is reflected back into the user's eyes. A system design using such a combiner obviously does not represent an optimum configuration due to this very high source brightness requirement. In addition, the 50 percent transmission of the ambient illumination seriously reduces nighttime vision through the combiner. An improved combiner for nighttime vision would transmit 80 percent and reflect 20 percent. This results in a maximum apparent background luminance of 8,000 foot lamberts and a symbology luminance of 6,400 foot lamberts on the HUD. Since only 20 percent of the source is reflected back into the user's eyes by the combiner, a 32,000 foot lambert source is required not even considering other optical efficiency factors. These figures indicate that a broad spectrum combiner is impractical for the high brightness HUD requirements.

One way to partially alleviate this problem with present HUDs is to use a dichroic (or trichroic) combiner. Reflection and transmission characteristics of dichroic or trichroic combiners are a function of the wavelength of the incident light. Typically, 90 percent of the light except for a narrow band (several hundred Å) is transmitted from the outside world. In this band, only 25 percent is transmitted, whereas 75 percent is reflected. Assuming the 10,000 foot lamberts background, 9,000 foot lamberts is transmitted. To provide the 1.8 contrast with 0.75 reflectivity, a light source of 9,600 foot lamberts is required. One disadvantage is that the source must be well matched to the spectral reflective wavelength of the combiner or the overall efficiency is lowered. Another disadvantage is the change in the coloration of the outside world as seen through the combiner. Since several hundred angstroms are notched from the outside scene, it will be tinted. Also, the narrower this band is made, the lower the overall efficiency of the source.

The second major consideration for HUD brightness/contrast is the source. The lamp illuminated reticles associated with the electromechanical HUD are unacceptable for the advanced HUD application due to their inflexibility and inability to display electro-optical video. The CRT is the source used in most HUDs today. The primary operational disadvantage of the CRT is the relatively low peak intensity achievable. To provide the 9,600 foot lamberts (with dichroic combiner), on the order of 5-watts of radiated power is required from the CRT phosphor. The conversion efficiency of a good phosphor in a CRT is approximately 5 percent, varying greatly with screen preparation, beam current density, and age. This efficiency would require a maximum beam power of 100 watts, where typical high brightness tubes may be rated around 10 watts. It is unlikely that such a tube could be built without a significant technological breakthru because of the beam power requirement and the phosphor loading in a conventional structure. One method that has been used on projection tubes has been to fabricate a water-cooled faceplate and to view the radiation from the rear of the tube through an optical porthole. Such a tube would be quite

large and very inefficient. It is concluded that the CRT is not capable of meeting the requirements of this application. The 2,000 foot lambert capability of existing HUDs is sufficient for viewing symbology only over a narrow field of view, at limited resolution, against a lower background brightness.

3.3.3 Accuracy

The accuracy of a head-up display is defined as the precision with which the symbols can be generated, superimposed upon a selected reference object, and retained while the unit is in operation. The contributing factors to the errors in a HUD are: (1) image displacement caused by the combining glass, (2) fabrication and alignment errors, and (3) parallax errors.

It is desirable that the combiner have the least possible effect on the apparent position and shape of objects viewed through it. This is especially important when one eye may be looking through the combiner while the other may be viewing the same scene directly. Both the refractive and on-axis reflective optics HUDs have flat combiners which have a negligible effect on the view of distant scenes. The off-axis reflective optics HUD uses an aspheric combiner and therefore has an effect on the appearance of scenes viewed through it. Analytical and measured data indicate an error of 0.5 to 5.0 milliradians, depending on viewing distance and on the point through which the combiner is being viewed.

For purposes of comparison, it is assumed that all the conventional optical HUDs are subject to the same tolerances in manufacture of the optical elements and have comparable alignment techniques. This may not be strictly true for the off-axis reflective optics, since aspheric optics pose particular manufacturing problems. A typical system would have errors due to manufacturing tolerances of ±0.2 milliradian.

Given sufficient freedom in the number of elements and size, an optical HUD can be designed and made to almost any accuracy. In a head-up display, with its severe limitation on space, some optical errors will inevitably remain. In general, the errors vary inversely with focal length. The principal concern with regard to optical errors in parallax or the change

in the apparent relative positions of the CRT symbology with respect to the outside scene when viewed from different eye positions.

The requirement to maintain 1-mrad accuracy and resolution over the entire field of view is met by today's limited field of view systems. However, when considering the use of conventional optical techniques to maintain this accuracy over a 60 x 45 degrees field of view, the design problems become almost insurmountable.

3.4 The Advanced Head Up Display Concept

It can be concluded from the preceding discussion that head-up displays utilizing conventional optics and CRTs cannot be made to meet the requirements of an advanced HUD. Better means are required to provide wider fields of view and higher brightness. It is also always desirable to improve reliability and reduce size and weight. Two new promising techniques appear to be directly applicable to the HUD application. These technologies are holographic optics and liquid crystal displays. They provide the potential for wider fields of view and higher brightness. The basic concept is shown in Figure 3-6. A holographic lens array provides the combiner function, while also providing part of the projection lens function. The liquid crystal (LX) array provides a light modulation function. This allows the use of an extremely bright light source. Also, the solid state nature of the LX matrix display, along with the light weight of the holographic optics promises to yield a head-up display of higher reliability and smaller size than presently possible.

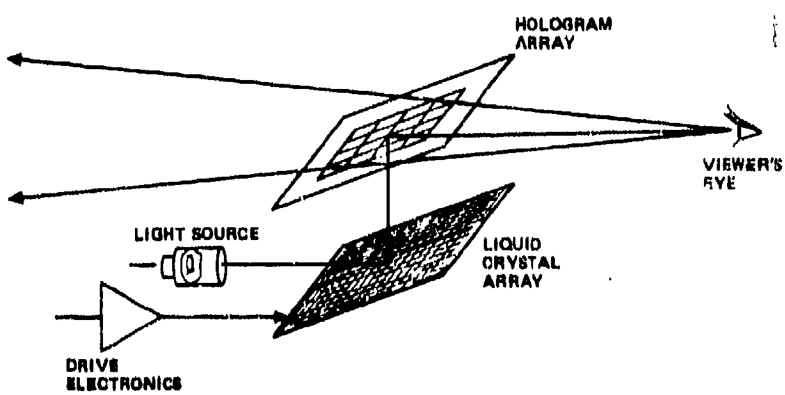


Figure 3-6. Advanced head-up display concept.

There are two basic characteristics of the holographic optics system that are distinctly different from the classical optics system that yield the potential improvements. First, the holographic lens provides the dual function of a collimating lens and a very narrow spectrum interference filter/combining glass. The importance of this dual function lies in the fact that complex conventional projection optics is not required. Also, by proper design of the holographic lens, compensation can be included for a significant portion of the image aberrations. This makes larger fields of view practical. These aberrations are functions of the associated optical components in the balance of the system and in the actual physical contour of the combining glass. This contour can be made to match the canopy contour. The second advantage is that the holographic lens is a particular form of a high resolution diffraction grating. The visible spectrum outside the narrow refraction band passes through the lens undistorted, while the image projected from the symbology source is collimated through the lens. This "see-through" design cannot be duplicated with conventional lens designs. This allows the source to be placed behind the combiner which results in a unique configuration. It also provides the desirable contrast improvement function of the dichroic on trichroic combiner.

To provide the degree of contrast required for bright symbology and sensor video in daylight, a very bright narrow band light source is required. The limitations of the cathode ray tube have been described, and the new solid state light emitting technologies of light emitting diodes and plasma panels are very limited in their light output. Even the laser is not capable of providing visible light scanned and modulated at the intensity required to provide a head-up sensor display in a 10,000 foot lambert condition. The scanned laser source does provide some of the characteristics desirable for this application. It is essentially monochromatic and hence meets that requirement of the holographic optics. It is also a well collimated beam of light resulting in high resolution. In fact the laser has been proposed as the light source for use with a holographic combiner in other HUD applications. Where only symbology is required, the laser can be deflection modulated to write the symbology much like stroke written symbology on a CRT.

Current production lasers are very inefficient sources of light (0.1 percent), requiring high electrical power to provide the intensity for this application (several kilowatts). Dye lasers in development exhibit higher efficiency (10 percent) but are very unreliable (10-100 hrs MTBF). Also, these high power lasers are bulky and require very precise optical adjustment. Any approach to higher efficiency lasers requires either cryogenic cooling or a narrow band optical pump source (or both). Also, the necessary deflection and intensity modulation to display sensor video requires complex electro-optical components. In summary, it can be concluded that although the laser provides an optimum source of coherent narrow band light, it is not suitable for this application. Several more attractive non-coherent sources of narrowband light are discussed in Section 6.0 of this report. A thallium arc lamp is the recommended baseline source. Given such a light, the problem becomes one of modulating its intensity over an area equivalent to the projected field of view.

The liquid crystal represents only one of the many materials that have been utilized as area light modulators. The advantages of the liquid crystal material over most other light modulation materials (i.e., lead zirconate titanate, potassium di-hydrogen phosphate, calcite, etc.) lies in its efficiency, sensitivity, and response time. A number of experimental panels have been fabricated using solid state drive circuitry to demonstrate the low drive voltage requirements and the display characteristics of a variety of liquid crystal materials. Other light modulation materials require much higher electric fields to exhibit comparable contrasts. Consequently, these materials cannot be driven by solid state integrated circuits due to the high voltage requirements. It is this liquid crystal property together with the development in LSI circuitry that make the flat panel matrix type display practical. A detailed discussion of liquid crystal display technology for application to the advanced HUD is presented in Section 5.0 of this report.

In the following sections of this report, more detailed descriptions and analyses of the various components are presented. Also, where appropriate, tradeoffs were performed in order to come up with a recommended configuration. Following these analyses, a baseline design is presented which indicates how the head-up display can be integrated into an aircraft cockpit.

4.0 HOLOGRAPHIC OPTICS; TRADEOFFS AND ANALYSES

4.1 Introduction

This section describes the Hughes Aircraft Company concept of the hologram lens array for head-up display applications. To define the technical background on which the hologram lens development task is based, this discussion describes the principles underlying the concept and the technological considerations involved in producing the hologram lens arrays.

4.1.1 Holographic Optics

The recording and use of three types of point-source holograms as optical elements with focal power is illustrated in Figure 4-1. Shown are

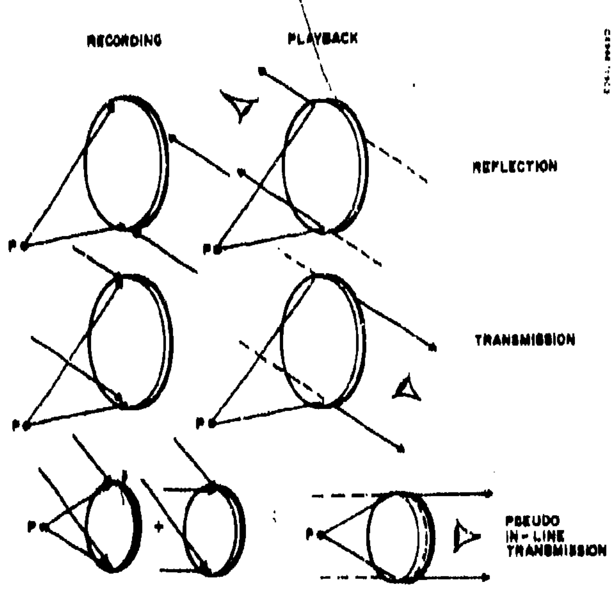


Figure 4-1. Generation and use of point-source holograms as focusing elements.

the two fundamental types of off-axis holograms, the reflection and transmission types, and a combination of two off-axis transmission holograms to make a pseudo-inline transmission hologram. The latter element has two interesting properties. First, it is approximately axially symmetric and therefore has lower distortion. Second, it has considerably smaller chromatic dispersion than the other two types. Its disadvantages include lower efficiency and more difficult fabrication. All three of these types can be used in HUD systems as will be shown.

The hologram is recorded by illuminating the light-sensitive recording material with two beams of light from the same coherent source of known wavelength. Both beams originate from point sources, one of which is at infinity. After the hologram has been recorded (and if necessary, processed), it can be illuminated by either of the two recording beams (at the recorded wavelength) to cause it to generate the other recording beam accurately. This playback step also is shown in Figure 4-1, wherein the diverging beam interacts with the hologram to recreate the collimated beam. A viewer looking into this beam sees the point P projected to infinity by the hologram. If the point source is displaced, the direction of the collimated beam changes by an angle equal to the angle subtended by the two point-source locations at the hologram. Therefore, the hologram has the ability to image an extended field. This field, however, consists of only the light of the recorded wavelength. To the rest of the spectrum, the hologram array acts as a plate of glass.

Although the hologram can image an extended field, it does not do so with unlimited accuracy. Inaccuracies appear as deviations of some rays in the collimated beam from the expected direction. These deviations are largest for rays near the edge of the hologram and increase as the displacement of the imaged point, P', from the hologram recording point P is increased, as shown in Figure 4-2. In other words, the angular errors increase as the field angle is increased and as the f number is decreased. If the maximum ray deviation as a function of the field angle is plotted, it is apparent, as indicated in Figure 4-2, that the error becomes 1 mrad at a half-field angle 3 to 5 degrees for typical hologram parameters. The

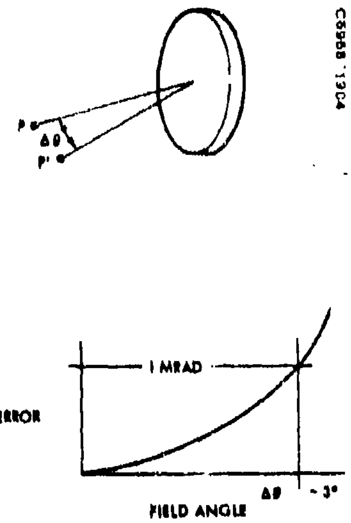
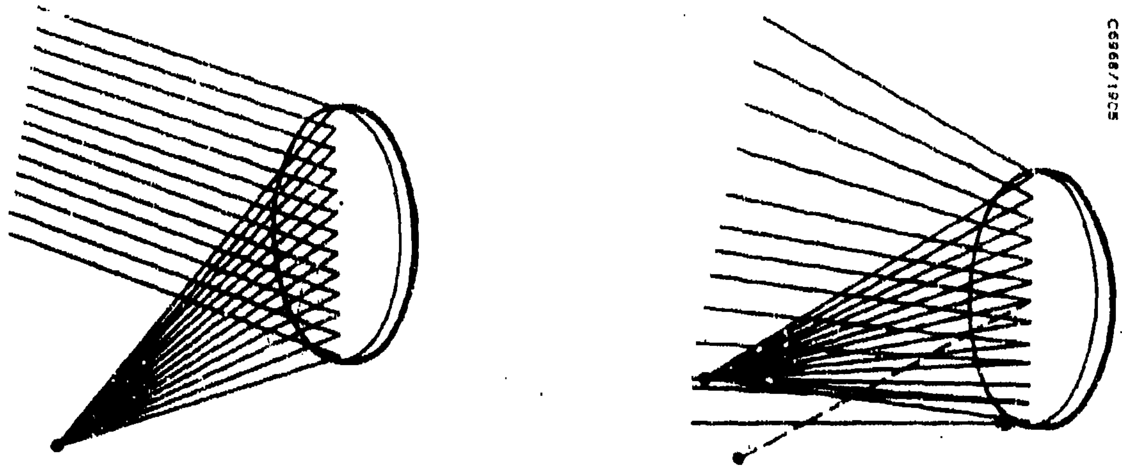


Figure 4-2. Angular errors of a typical holographic optical element.

advanced HUD requirement is to provide image resolution and accuracy of better than 1 mrad over field angles of 30 to 45 degrees therefore, a single hologram optical element has limitations as the projection element for such displays.

Effects of the off-axis aberrations indicated schematically in Figure 4-3 depend strongly on applicable hologram parameters, particularly the off-axis angle, the asymmetry angle, and the size of the viewing pupil. For viewing with the eye, the effects of the aberrations are generally to introduce distortion rather than a loss of resolution, because over a bundle of rays the size of the eye pupil, the ray directions do not vary appreciably. However, as pupil location is changed, the average ray direction changes, causing the apparent image location to shift.

Another characteristic of these holograms is that as the object point is moved from the hologram construction location, the efficiency of conversion of the diverging beam into the collimated beam decreases. This loss of optical efficiency arises because the conversion process is Bragg diffraction from the recorded fringe planes in the hologram medium, a process sensitive to the beam angles. This angular dependence of optical



(a) On-axis reconstruction (b) Off-axis reconstruction

Figure 4-3. Off-axis aberrations.

efficiency effects the optical efficiency of the single hologram lens as a function of the field of view. For typical geometries, the angular width of the efficiency curve is 5 to 10 degrees in the plane containing the optical axis and somewhat larger in the perpendicular plane. This fact also places a limitation on the performance of a single lens.

4.1.2 The Holographic Array Concept

To obtain the required performance in a head-up display, it is necessary to use a multiple-element hologram lens. A single element system cannot provide the required optical efficiency, and the more nonlinear distortion of the single element leads to much larger binocular disparities. This behavior is not surprising, since a single hologram optical element, like a single lens or mirror element, has large off-axis aberrations. Therefore, a multiple-element hologram optics technology is required, just as a multiple-element technology is required for ordinary optical elements.

To avoid the difficulties of the single-element system, the hologram array technique indicated in Figure 4-4 has been developed. This array concept is based on the fact that in an optical system like the HUD, rays from a single point in the field of view that enter the viewer's eye come through only a small part of the projection aperture. In other words, different parts of the projection aperture correspond to different parts of the field of view. This means that the angular field and the projection aperture can be divided into small segments, and one can synthesize a small hologram in each segment of the aperture to form a high quality image over the corresponding segment of the field of view. If these small holograms are accurately aligned, they project a continuous high-quality image over the entire large field of view.

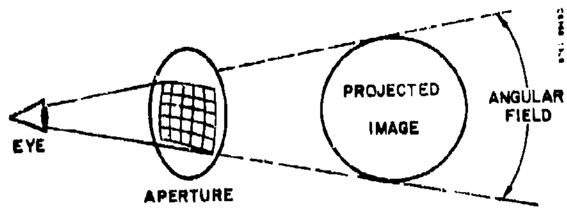


Figure 4-4. The hologram array concept.

The Hughes array technology provides a configuration where the parameters provided by multiple hologram elements can be adjusted to provide good system performance. Just as with ordinary optics, effective and efficient hologram optical system design requires expert knowledge and experience of what configuration to use and which parameters to vary, as well as digital computer programs to perform multi-variable optimizations.

The fundamental advantages of this array configuration are to reduce the loss of resolution and the increase in distortion due to off-axis aberrations and to obtain a more uniform optical efficiency across the projection

aperture. To realize these advantages, it is necessary to overcome two difficulties associated with implementing the array concept. First, an array exhibits distortion that can vary with eye position, although usually far less than for a single hologram. Second, the presence of intersections between adjacent holograms in the array introduces the possibility of discontinuities in the image if proper alignment is not achieved. Utilization of the fundamental advantages of the array over the single lens can be achieved by a system design that eliminates or adequately reduces the imaging errors that occur in the array approach in a configuration that is acceptable from a systems viewpoint.

Design of an array of holograms for use in projecting an image to infinity is based on two criteria: first, the image is viewed from a certain location (the pupil location); and second, adjacent elements of the array provide a continuous image to the observer. The first criterion is met by forming each element with a collimated beam that passes through the pupil location and a diverging beam from a point source located in the system source plane. The second criterion is met by choosing the locations of the point sources such that the fringe planes in two elements are parallel at the intersection of the elements, thereby providing a "mirror without a kink." A digital computer program is used for performing this design function.

Later in this section, the basic design approach is described in detail. It should be noted here, however, that this basic design has unaligned intersections between hologram elements of the array at which localized distortion can occur even when there is no average system distortion. In a proper system design, this local distortion is reduced to insignificant proportions. Realization of the optimum design requires detailed analysis and evaluation of the array beyond the scope of the program.

4.2 Preliminary Systems Considerations

4.2.1 General

The HUD optical system design must be closely tied to the operational system configuration as well as to performance requirements. Figure 4-5

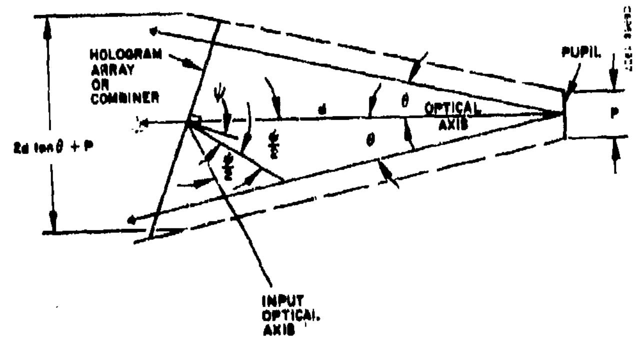


Figure 4-5. The basic HUD system configuration.

shows the basic system configuration that is required. The image is viewed along an optical axis from a viewing pupil of dimension P. The distance between the viewing pupil and the input surface is d. The input surface here is assumed to be a flat combiner plate or a flat hologram array. For a total angular field of view of 2θ, the input surface must project to a vertical height of $2d \tan \theta + P$.

The input optical axis is deviated by an angle of $180-\phi$ degrees to coincide with the viewing optical axis. If the input surface is a combiner plate, its normal must bisect the angle ϕ, requiring the asymmetry angle ψ in Figure 4-6 to be equal to zero. For a hologram array at the input surface, we need not require $\psi = 0$. Our studies show that for $\psi>0$, as in Figure 4-5, the image is distorted, while for $\psi<0$ the field of view is distorted. In both cases the amount of distortion increases as the off-axis angle ϕ is increased.

One major factor in this system configuration is the size of the components involved. For example, if we use a flat plate normal combiner, the projection aperture becomes quite large even if it is not tilted relative to the optical axis. This is indicated in Figure 4-7, where the shaded area is the line-of-sight volume that cannot be obstructed. Note that as the off-axis angle ϕ is decreased, the required projection aperture (i. e., the distance between the extreme field lines) increases rapidly to keep the projection aperture outside the line-of-sight volume. The projection aperture is minimum for $\phi \approx 90$ degrees, but still has a size of about 40 x 30 inches for a 60 x 45 degrees field of view.

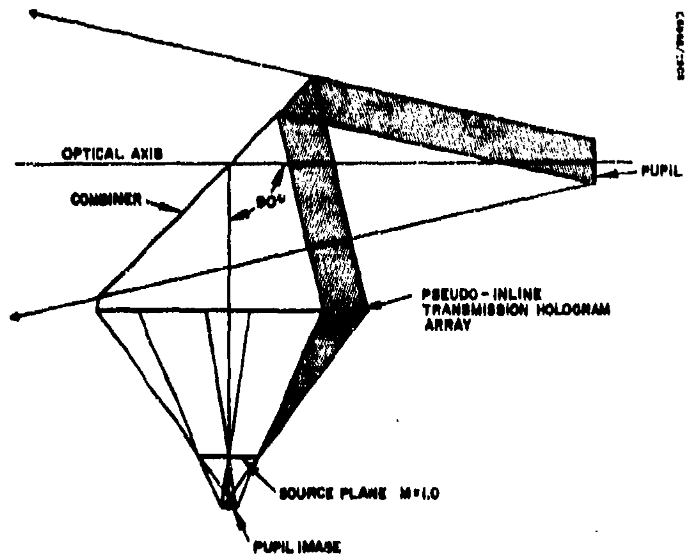


Figure 4-6. System geometry using a pseudo-inline transmission hologram array and a flat combiner plate.

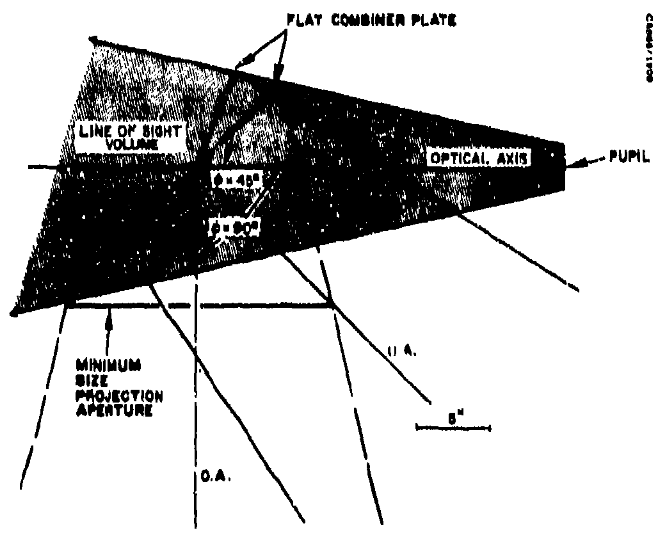


Figure 4-7. The relationship of projection aperture size to the system geometry when a flat combiner plate is used.

If the input surface is a hologram array (i. e., the input surface is also the projection aperture), the projection aperture is somewhat reduced in size. However, the projected size is still approximately 30 x 20 inches, and a usable system requires $\phi > 0$ so the actual size is larger than the projected size.

For systems with the hologram array serving as the projection aperture, the object or source plane (liquid crystal image plane) subtends approximately an angle 2θ (the field angle) at the array. If the spacing between the source plane and the center of the array is f_o, the size of the source plane is approximately $2f_o \tan\theta$. A 25 degrees FOV configuration employing a reflective hologram array is shown in Figure 4-8. Similar arguments can be made for a transmission hologram array, and an example of the latter type of system is shown in Figure 4-9. The important thing to note is that the rapidly expanding line-of-sight volume requires that the input optical axis make a larger angle with the viewing optical axis. In the system shown in Figure 4-8, the angle is 45 degrees, compared to 18 degrees for the reflection hologram array. This is a definite disadvantage, because the increased distortions caused by this larger angle are difficult to remove.

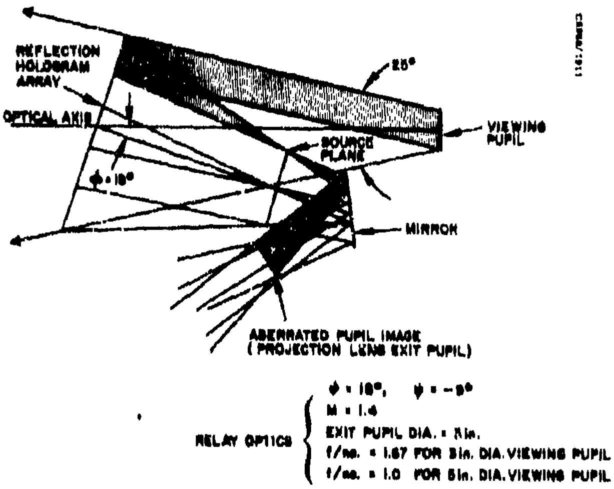


Figure 4-8. System geometry using a reflection hologram array/combiner plate with ϕ = 18 degrees and ϕ = -9 degrees and with the optimum input image magnification of 1. 4 and a folding mirror.

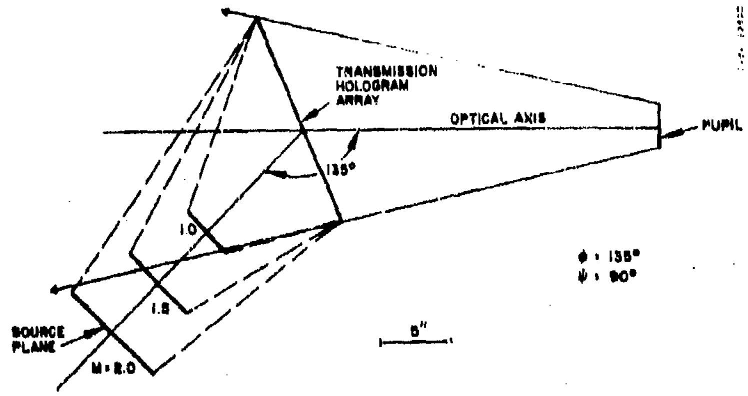


Figure 4-9. System geometry using a transmission hologram array/combiner plate with ϕ = 135 degrees and ψ = 90 degrees.

The pseudo-inline transmission hologram array, illustrated in Figure 4-6, provides minimum distortion at the expense of complexity. In place of the single hologram array in the earlier systems, two matched transmission hologram arrays are required to form the pseudo inline element. A large combiner plate is also required.

4.2.2 Relay Lens Characteristics

A major consideration in the proposed HUD system is the size of the liquid crystal matrix source. Technically, it will ultimately be possible to provide this matrix on a 3 inch by 4 inch sub strate to cover a 60-x 45-degrees FOV. However, for direct array projection, the matrix would have to be placed approximately distance

$$f_o = \frac{1.5}{\tan 22.5^o} \approx 3.8 \text{ inches}$$

from the array and would therefore be directly in the viewing volume of the display. There are two possible solutions to this difficulty. First, increase the size of the liquid crystal matrix, and second, project a virtual image of the matrix into the system, using an auxiliary relay lens. In this section, the requirements placed on the relay lens by the system parameters are

examined. Although the concept has not been investigated in detail, it is conceivable that a holographic optical element could be used to provide this relay lens function.

For the purposes of this discussion, it is useful to simplify matters by unfolding the optical system, as shown in Figure 4-10. The system geometry when using the relay lens is indicated in Figure 4-11, where the component spacings are given in terms of the system parameters. The dependence of the pupil size on these spacings and on the aperture A of the relay lens are fixed by the requirement that the exit pupil of the relay lens (the indicated aperture A) be located at the position of the image of the system viewing pupil formed by the array. The system viewing pupil is the image of the relay lens aperture formed by the array, and fixing the system pupil therefore fixes the characteristics (aperture and focal length) of the relay lens. The required relationships can be determined approximately by applying the thin lens formula,

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q}, \tag{4-1}$$

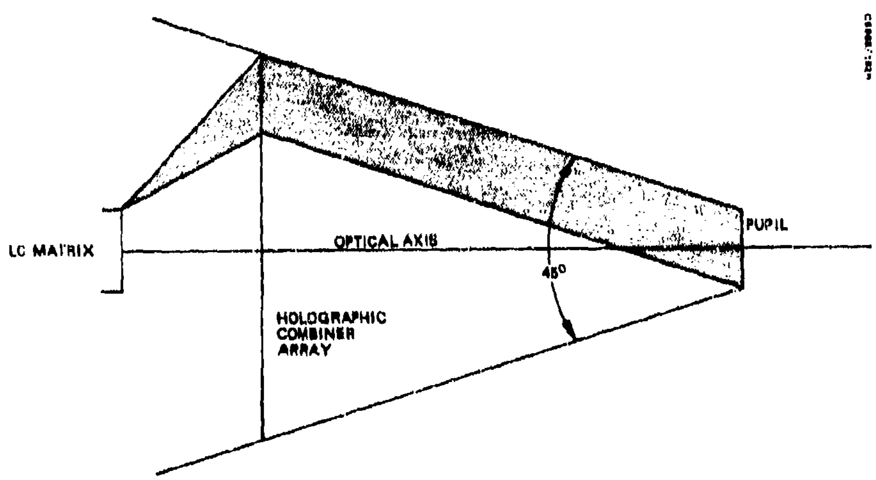


Figure 4-10. Optical system.

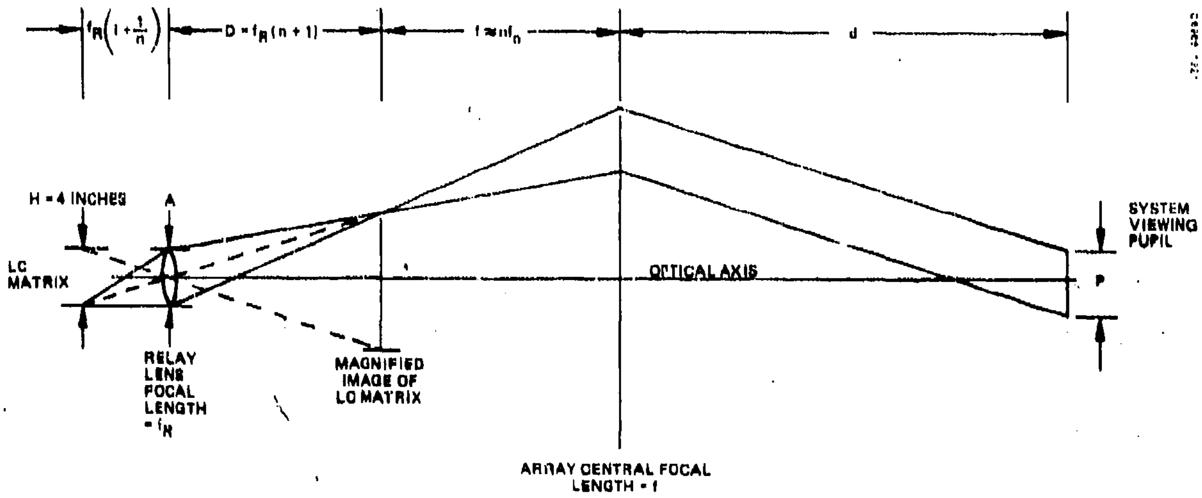


Figure 4-11. Optical system geometry.

to the array and the relay lens, where f is the proper focal length and p and q are the object and image distances, respectively. The relationships,

$$n = q/p \,, \tag{4-2}$$

$$q = f(n+1) \,, \tag{4-3}$$

$$p = f(1 + \frac{1}{n}) \,, \tag{4-4}$$

where n is the image magnification can also be used. For the image of the system pupil formed by the array,

$$\frac{1}{q_A} = \frac{1}{f} - \frac{1}{d} = \frac{1}{nf_o} - \frac{1}{d} \,, \tag{4-5}$$

and

$$A = \frac{q_A P}{d} \tag{4-6}$$

are the pupil image height and thus the aperture of the relay lens. Then in Figure 4-11,

$$D = q_A - nf_o = f_R(n+1). \qquad (4\text{-}7)$$

From (7), the focal length of the relay lens is

$$f_R = \frac{D}{n+1} \qquad (4\text{-}8)$$

Therefore, the f/number of the relay lens, f_R/A, which is a meaningful descriptive parameter of the relay lens, is

$$F = f/\text{number} = \frac{Dd}{q_A P(n+1)} = \frac{nf_o}{(n+1)P} = \frac{nH}{2(r+1)P\tan\theta_v}, \qquad (4\text{-}9)$$

where H is the height of the liquid crystal matrix and θ_v is the half angular vertical FOV. For very large n, the f/number becomes

$$F = \frac{H}{2P\tan\theta_v}. \qquad (4\text{-}10)$$

For H = 3 inches, P = 5 inches and θ_v = 22.5 degrees, the relay lens f/number, from 4-10, is 0.75. This would be a difficult lens to design, even for the relatively low resolution requirements of the HUD system, because it also must cover the 60-x 45- FOV of the display. The actual baseline design described later in this report employs a less dense 6 x 8 inch liquid crystal array. This results in an f/1.5 relay lens which is easily obtained.

Another consideration is that for $d \approx n f_o$, D, the relay lens, and the system length becomes very large. Typically, $nf_o \sim 10$ to 15 inches and $d \sim 25$ inches, so this is not a serious problem.

The overall system length and the size of the relay lens can be reduced by introducing a field lens at the position of the magnified image. It is straightforward to show that the relay lens focal length is decreased in the same ratio as the aperture, so that the f/number remains constant.

There is, therefore, a direct tradeoff among the system parameters, according to equation (4-10), where a desirable relay lens tends to imply a large liquid crystal matrix, a small pupil, and/or a small field of view.

4.2.3 Use of Canopy as Substrate for the Hologram Array

There is no a priori reason why the aircraft canopy cannot be used as a substrate for the array. By the nature of the hologram elements, their optical characteristics do not depend on the substrate curvature. There are two minor disadvantages associated with this configuration. First, the aberrations of a curved substrate hologram are somewhat larger than those of the corresponding flat plate hologram; and second, the curved-substrate array is more difficult to fabricate than a flat plate array. The aberration problem should not cause any deterioration of system performance, because the curvature is rather small. The fabrication problem requires proper design techniques, fabrication apparatus, and the ability to form uniform, high quality films of the recording material on the canopy surface. These techniques are being developed for other applications, and there should be no difficulty in extending them to the HUD geometry. Also, the acrylic plexiglas material commonly used for canopy fabrication is suitable material for the substrate of the holographic optical elements.

With an optical element on the canopy, there arises a question of performance during operational stressing of the aircraft. If the canopy behavior in operational conditions is known, the effect on image quality can be readily ascertained, because the holograms will behave like simple mirrors in this regard. For small deformations, the angular shift in the image location will be equal to twice the change in the direction of the normal to the canopy surface.

There is possibly a major advantage to a configuration that uses the canopy as the array substrate, viz., the curvature can be used to effectively cancel distortion in the projected image. As will be shown later, distortion can be viewed as resulting from a changing focal length across the aperture. For flat plate configurations, it is possible to remove the average variation through proper design, but there remain local variations that cause local distortions in the image. It appears that an inward-curving array substrate could substantially reduce these local distortions, particularly when used with a curved source distribution. If the source distribution is a projected image, then the relay lens design is simplified as well.

4.2.4 Small Element/Large Pupil Effect

In the hologram array optical system, there are two types of errors that have to be considered. One is the error due to off-axis aberrations of a single hologram, and the other is systematic errors due to the geometry of the array. These types of errors can be interpreted in terms of system operation.

Figure 4-12 shows the first type, which occurs when one views different parts of the image through the same point on the array. The image quality is then determined by the off-axis errors of the single element and the parameters (geometry) of the system.

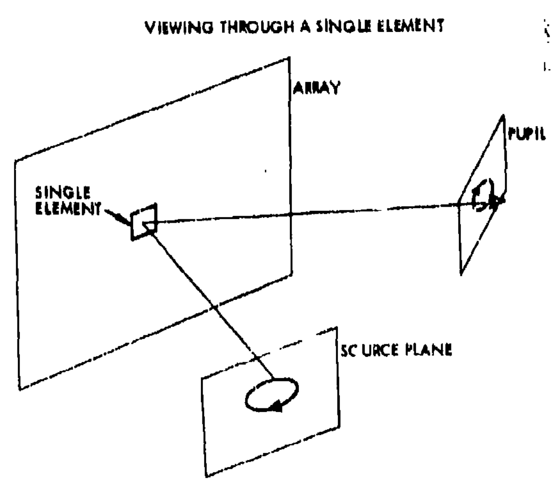


Figure 4-12. Single hologram angular errors.

Figure 4-13 indicates the occurrence of the second type of error. This type of error is prominant in HUD systems where the viewing pupil size is larger than the size of the hologram elements making up the array. Thus, the effects due to this type of error are termed "small element/large pupil" effects. In this situation, as the eye moves in the viewing pupil but remains fixated on a single point in the image, that point is sequentially viewed through a series of different elements in the array. In the limit of a very large pupil and very small elements, the image characteristics are

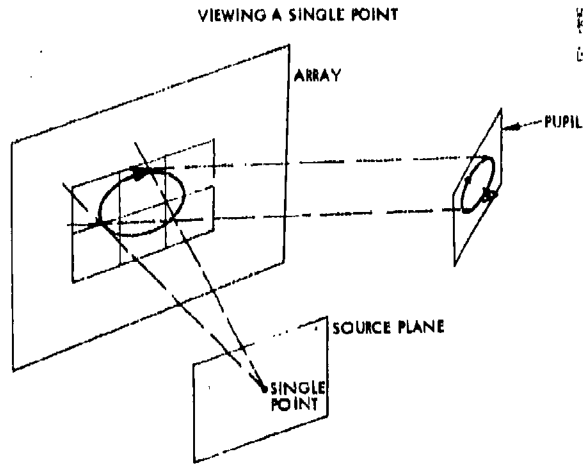


Figure 4-13. Large pupil/small element errors.

determined entirely from the array design. In practice, the off-axis aberrations of each element also play a part. The particular errors of concern here are binocular disparity between two eyes viewing the same image and collimation errors, i. e., differences in apparent image direction through different parts of the viewing pupil. Along with optical efficiency and image distortion, the collimation errors and binocular disparity errors are the major concerns in evaluating HUD system performance.

4.3 Recording Material Tradeoff

The selection and development of an appropriate material to hold the interference fringe patterns is a major consideration for the HUD hologram lens system. The choice of a material is restricted by several mandatory material characteristics. In this section, the necessary properties will be examined, a survey of holographic materials will be made, and potential material candidates for the HUD arrays will be identified.

4.3.1 Requirements for HUD Array Recording Materials

Volume, Phase Hologram

The requirement that the holographic lens must have greater than 90 percent light diffraction efficiency dictates that the material must be capable of recording a thick (volume) and phase-modulated hologram. The theoretical maximum diffraction efficiencies for thin amplitude and thin phase holograms are 6.25 and 33.9 percent, respectively, whereas thick phase holograms can achieve up to 100 percent efficiency.

Film Thickness and Index Change

The geometrical constraints of the HUD system determine both the maximum allowable film thickness and minimum refractive index change in the material, since these factors have a direct bearing on a hologram's angular selectivity. Typically, a ±3 degree field coverage is required from each element of a hologram array for display purposes to cover the desired field with an adequate number of elements. To calculate the film thickness necessary to satisfy this condition, apply equation (4-11)

$$\Delta \theta_R \approx \frac{K\lambda}{2\, dn \sin \theta} \tag{4-11}$$

where $\Delta \theta_p = 3$ degrees, the angle of half-width at half-maximum reflection, $K \approx 3$, a factor determined experimentally from dichromated gelatin holograms, λ is the light wavelength, d is film thickness, $n \approx 1.5$, the refractive index, and $\theta \approx 30$ degrees, the angle between the normal to the hologram plane at the point of reflection and either the incoming or reflected rays. Performing the substitutions, the maximum allowable film thickness becomes approximately 25 µm.

For a phase hologram, the film thickness dictates the minimum refractive index change necessary to develop a given diffraction efficiency. Using equation (4-12) for a reflection hologram,

$$n = \tan h^2 \frac{\pi \Delta nd}{\lambda \cos \theta} \tag{4-12}$$

and substituting the value $\eta = 90$ percent, the diffraction efficiency, and solving for Δn, the required index change, a value of 0.0127 is obtained.

The thickness and index change requirements can be somewhat relaxed by modifying the array geometry (e.g., making θ smaller), but large deviations from the thickness or index limit can only be made by sacrificing efficiency or angular response of the holographic lens.

Additional Requirements

Additional recording material requirements for the hologram lens are listed below:

1. Permanence - The holographic lens must be stable with respect to efficiency, reflection wavelength, and transparency in wavelengths outside the operation reflection region.
2. Specific operating peak reflection wavelength.
3. Resolution - The material must have a resolution of at least 5000 cycles/mm to qualify as a reflection hologram material with a typical 1.5 bulk refractive index.
4. Environmental endurance - The hologram's operational parameters must not change with changes in environment as specified for MIL-5400L class 2 materials.
5. Optical quality and noise - The material must transmit more than 90 percent of incident light outside the operational reflection range, scatter less than 5 percent, and must not distort the real-world images.

4.3.2 Survey of Holographic Materials

Presently, many materials exist in which holograms can be recorded, but of these only a few can be seriously considered for the present application in light of the criteria listed above. The criterion of a thick phase material immediately disqualifies the bulk of holographic materials, such as silver halide emulsions (conventional development), thermoplastic zerography materials, transient photochromics, etched photoresists, kinoform materials, and magneto-optic materials. A survey was made of the remaining materials, and they are roughly grouped in classes in Table IV-1, where most of their important characteristics are listed.

TABLE IV-1. PHASE HOLOGRAPHIC MATERIALS AND PROPERTIES

Material Type	Refractive Index Change (X. 01)	Diffraction Efficiency (%)	Typical Exposure (mJ/cm^2)	Resolution (cycles/mm)
Array Requirements	>1.27	>90	<200	>4700
1. Photopolymers				
a. Ba Acrylate	1.0	45	0.6	3000
b. Optical Cement	0.5	98	8200	>5000
c. Dye Sensitized Photoresist	—	10	10000	>4000
2. Direct Optical Effect Materials				
a. Lithium Niobate	0.004	40	10^5	4000
b. Arsenic Sulfur Glass	—	18	9000	—
3. Gelatin Systems				
a. Bleached Silver Halide Emulsions	2.0	64	0.11	>2000
b. Dye-Alcohol Sensitized Gelatin	—	—	—	>4000
c. Dichromated Gelatin	2.0	>90	30	6000
d. Dye Sensitized Dichromated Gelatin	2.0	>50	2000	>4000

Each material's comparative advantages and disadvantages are evaluated below. Those materials showing greatest promise with least development time and expenditure are then identified. Incomplete data on material properties will tend to disqualify a material, since additional investigation would be necessary to determine its practicability.

The first example of a photopolymer, barium acrylate, fails to satisfy the present system requirements in resolution and high diffraction efficiency, and it has stability and environmental disadvantages in its present form. A major research effort would be required to raise these parameters to acceptable levels; hence, this material will not be considered in the present program.

A recent development by Files has shown that commercially available optical cements can be dye-sensitized and used to fabricate high-efficiency, low-noise thick phase holograms. When considering the current application, two major disadvantages become apparent: index changes of only 0.005 have been realized and several J/cm^2 are required to achieve diffraction efficiencies of 90 percent in the reported composition. However, favorable material characteristics of low noi . high resolution, self-development and good environmental stability warrant further exploration of this material.

Recent work at Hughes has shown that dye-sensitized photoresist, a polyvinyl cinnamate compound, is capable of recording reflection phase holograms with He-Ne laser light. Due to the recency of the development, little quantitative data is available; hence, it will not be considered further.

The two examples of direct optical effect materials, lithium niobate and arsenic sulfur glass, offer several presently insurmountable material deficiencies, which are typical of this class of materials. Very large exposures are required, only small index changes can be achieved, and reported maximum diffraction efficiencies are far from the required 90 percent level. Furthermore, many of these materials form holograms that are adversely affected by exposure to visible light. There are also fabrication difficulties for the crystal or quasi-crystal materials in forming a large head-up display. The direct optical effect materials have been included in the survey for the sake of completeness, but their practicability in the

present application is doubtful. As a class of thick phase holographic materials, the gelatin materials offer the most promise in the current application. Both obtainable index changes and resolution are well within the required limits.

With bleached silver halide emulsions, Upatnieks and Leonard report that 64 percent efficiency can be achieved in 18 μm thick films for two beam holograms, and it is believed that higher efficiencies can be accomplished by increased film thickness. The primary disadvantage of this material lies in the film thickness decrease upon plate processing. Upatnieks and Leonard have found that the Kodak 649F emulsion typically shrinks 15 to 18 percent after fixing and drying due to the removal of material from the film. This means that the reflection hologram fringe would make a corresponding wavelength shift. For example, a hologram recorded at 632.8 nm would change its peak reflection wavelength to about 530 nm after processing. Glycerol or triethanolamine have been used to control the shrinkage of the emulsion to eliminate color shift, but this process tends to make the bleach products less stable and darken with exposure to light. Because of these problems, this technique has been eliminated as an approach.

Dye-alcohol sensitized gelatin, a very recent Hughes development, has red light sensitivity, resolution >4,000 cycles/mm, and grating permanence upon development after exposure. Unfortunately, as is the case with dye-sensitized photoresist, the present paucity of quantitative data precludes immediate application of this material.

Dichromated gelatin (DCG) is best available material for the array application. This material has proved very successful in the Hughes Helmet-Mounted Display, operating in the green spectral region. Its spectral sensitivity is limited to blue and green light, and the longest exposure wavelength is restricted to about 520 nm. The final material in Table IV-1, dye-sensitized DCG, can be used for systems requiring material response at longer wavelengths. Its properties are very similar to those of normal DCG.

As shown in Figure 4-14, dichromated gelatin is capable of a high optical efficiency, small dichroic effects, and low scattering, all of which are desirable characteristics for display applications. However, the dichromated gelatin is insensitive at the operating wavelength of the display; this requires exposures to be made with an argon ion laser at 488 or 514.5 nm, with proper processing techniques to expand the gelatin layer so that the response is shifted toward longer wavelengths. These techniques have been studied with the result that the response can be tuned to the desired wavelength. Useful lifetimes of a few thousand hours should be attainable.

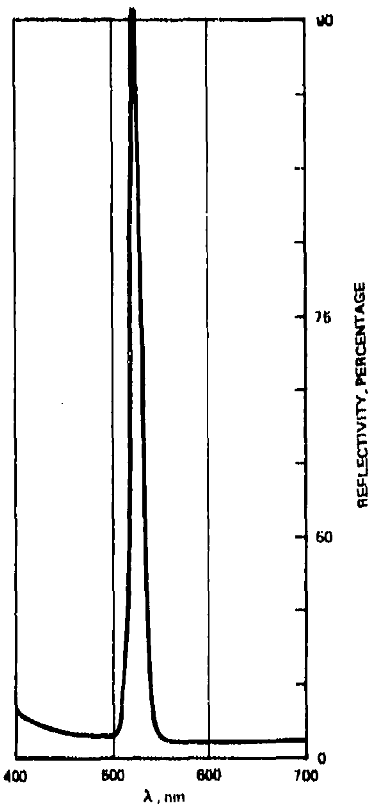


Figure 4-14. Typical spectral efficiency.

4.4 Design of Hologram Arrays for HUD Systems

4.4.1 Basic Design Techniques

In this section some basic design criteria for hologram lens arrays are described. The hologram arrays are discussed in the context of the reflection geometry of Figure 4-8, but the same characteristics apply to the transmission geometries of Figures 4-6 and 4-9 as well.

The basic array formation process is based on alignment of adjacent hologram elements in the array by controlling the fringe orientation. The relationship of fringe-plane orientation to the directions of the hologram-forming beams is indicated in Figure 4-15. In a small volume, the directions of the beams are well defined, and these two directions define a plane in space. The fringe planes formed by these two beams are normal to the plane of the two beams, and the fringe planes bisect the angle between the two beams. Therefore, the normal to the fringe planes lies in the plane of the two beams and bisects the angle formed by one beam direction and the reverse of the other beam direction. If the directions of the two formation beams are specified by unit vectors $\vec{R}$ and $\vec{O}$, then the unit vector normal to the fringe planes is $\vec{N}$ and

$$\vec{N} \propto \vec{O} - \vec{R} \, . \qquad (4\text{-}13)$$

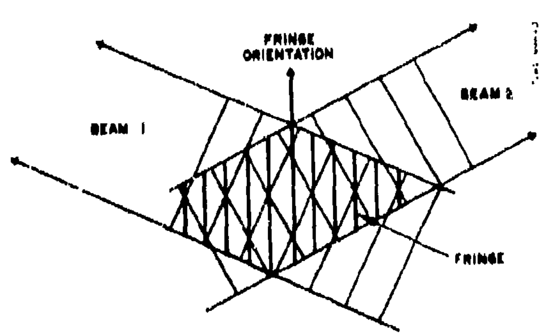


Figure 4-15. Hologram fringe orientation.

Two sets of fringe planes defined by their normals

$$\vec{N}_1 \propto \vec{0}_1 - \vec{R}_1 \tag{4-14}$$

and

$$\vec{N}_2 \propto \vec{0}_2 - \vec{R}_2 \tag{4-15}$$

can therefore be aligned as desired by making $\vec{N}_1$ parallel to $\vec{N}_2$, or

$$\vec{N}_1 = \vec{N}_2 . \tag{4-16}$$

The directions $\vec{R}_1$ of the collimated beams used to form the hologram elements are specified by the set of lines connecting the centers of the hologram elements to the center of the pupil area. One object point direction, $\vec{0}_1$, is specified by establishing the center of the system source plane and the center of the array plane. The other object point directions $\vec{0}_I$ are chosen through equations (4-13) and (4-14) to satisfy the alignment conditions, equation (4-16). This geometry is indicated in Figure 4-16. It should be

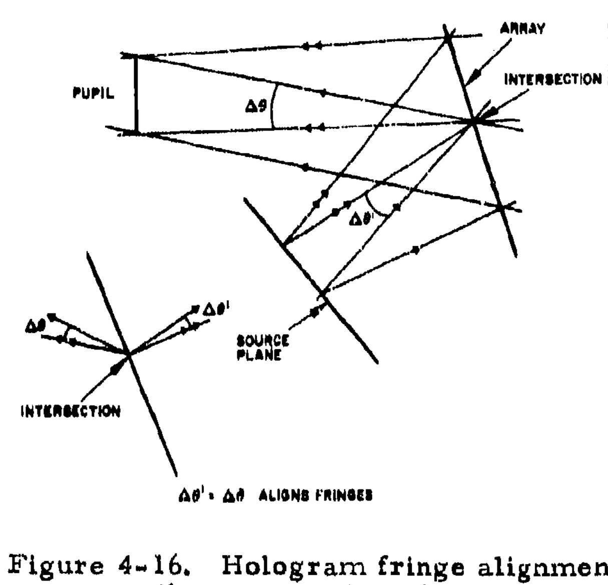


Figure 4-16. Hologram fringe alignment at the intersection of two array elements.

noted that $\vec{R}_1$, $\vec{0}_1$ need not lie in the same plane as $\vec{R}_2$, $\vec{0}_2$ to keep $\vec{N}_1 = \vec{N}_2$. Also, in an N x M array, there are 2 NM - (M+N) intersections, but only NM - 1 alignments available, so not all intersections in the array can be aligned unless N or M is equal to 1.

A suitable choice for aligning a 5 x 5 array is shown in Figure 4-17, where the central vertical column is first aligned and then each horizontal row is aligned to the corresponding element of the central vertical column. The unaligned intersections are indicated by broken lines.

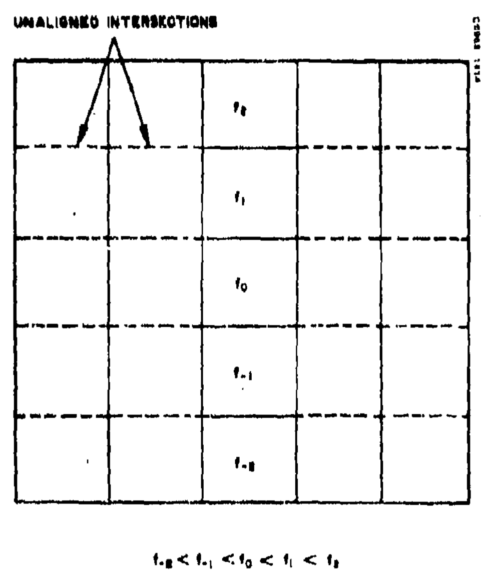


Figure 4-17. Configuration of an aligned array.

4.4.2 <u>Optical Characteristics of the Basic Design</u>

The effect of the above formation procedure on the optical characteristics of the array depends on the system geometry. For an off-axis system with the source plane perpendicular to the optical axis, such as indicated in Figure 4-16, the focal lengths of the elements vary across the array as indicated in Figure 4-17. The changing focal length introduces distortion into the projected image. This distortion is a property of an

imaging element that has a varying focal length over its aperture. However, the array has discrete elements; hence, the distortion may be discontinuous. In fact, the image of a set of three parallel vertical lines as seen in an array having this geometry is indicated on an exaggerated scale in Figure 4-18, where the expected trapezoidal distortion is present along with discontinuities (out of focus) at the intersections of the array elements.

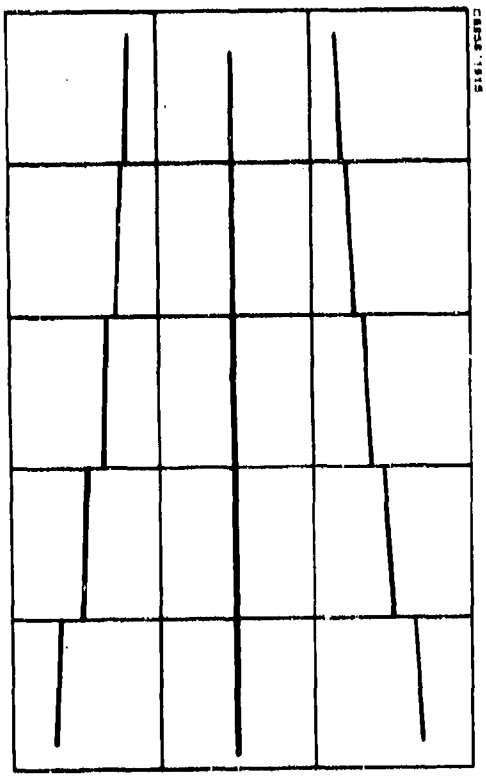
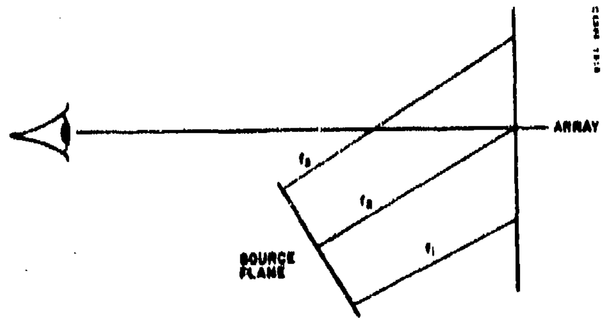


Figure 4-18. Exaggerated simulation of the discontinuous trapezoidal distortion appearing in the projected image of three parallel vertical lines.

The variation of focal lengths across the array in this geometry is depicted again in Figure 4-19. For a small spatial offset $\delta\ell$ in the source plane, an apparent angular offset $\delta\theta$ will be present in the image such that $\delta\theta/\delta\ell = 1/f$. Because f varies across the array, there is a corresponding variation in $\delta\theta/\delta\ell$, "the angular magnification." Another way of stating this effect is that there is a variation of optical curvature across the array such that where the focal length is smaller the curvature is larger. If the optical



$f_1 < f_2 < f_3$

Figure 4-19. Origin of the discontinuous trapezoidal distortion.

configuration of the array is drawn corresponding to Figure 4-17, the result is indicated in Figure 4-20. In this representation, the origin of the discontinuous distortion is clearly the varying curvature of the mirrors. Because of the discrete nature of the hologram array, this discontinuous distortion can be conveniently decomposed into the two components of "global" distortion due to the variation of the focal length from hologram to hologram, and local distortion, due to the variation of the focal length within a hologram.

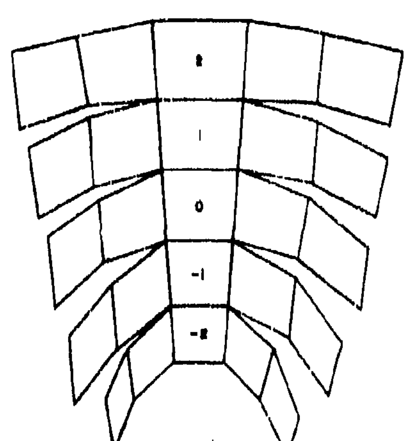


Figure 4-20. Optical topology of an aligned array.

The global distortion can be corrected, even in the off-axis system, by a proper orientation of the source plane. For a given geometry, an orientation of the source plane can be found such that the central focal lengths of the elements are nearly equal as shown in Figure 4-21. The extent to which the central focal lengths can be equalized depends on the system geometry, and this is one factor in choosing the system configuration. Typically, the global distortion can be reduced by a factor of 10 or more. Residual variation depends on other array parameters so that extensive calculations are required to provide a highly optimized array design.

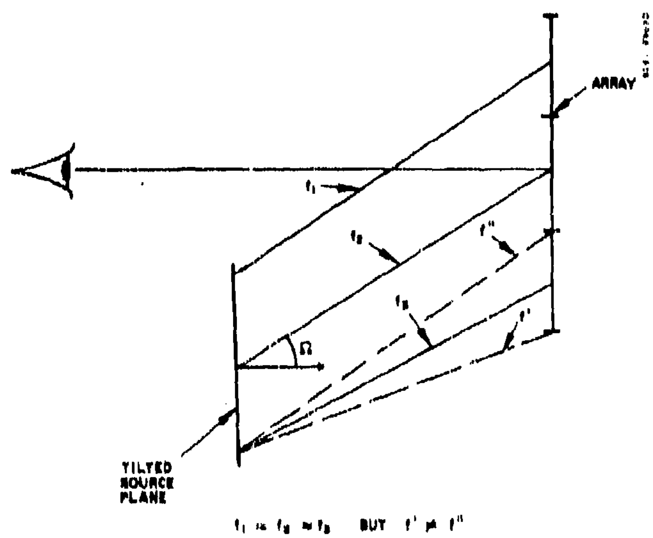


Figure 4-21. Correction of global distortion in the array image.

The realization of equal central focal lengths (i.e., the distance from the construction point source to the center of the element) provides a projected image with low average distortion. However, localized distortion still can be present in the image. As pointed out above, this localized distortion occurs, because the focal length varies over the aperture of an individual hologram even though the central focal lengths are constant. This is indicated in Figure 4-21, wherein it is apparent that $f' \neq f''$. The size of

the local distortions can be estimated from the array geometry. For an off-axis angle ϕ of 40 degrees, the local distortions can be several milliradians.

4.4.3 Improved Design Techniques

Correction of local distortion is the main task of hologram array design. A number of methods for correcting the local distortion caused by unaligned intersections in the array include the following:

1. Larger number of elements in the array,
2. Decreased off-axis angle,
3. Use of a linear array (single column),
4. Distribution of the misalignments,
5. Use of curved source surfaces, and
6. Use of a "warped" design.

Increasing the number of elements in the array, particularly the number of rows, is a straightforward approach which reduces the angle subtended by the individual hologram lens at the source plane and thereby reduces the local variation of focal length. The main disadvantage is fabrication of the array.

Decreasing the off-axis angle is another straightforward method, because the local distortions are approximately proportional to the sine of this angle. This approach also has the advantage of decreasing the amount of average distortion that needs to be removed (i.e., the amount of source plane tilting required), which simplifies the relay optical system design. However it possesses a disadvantage when considering the installation in the cockpit, since the source can get folded back into the field of view.

If a single column (linear array) of holograms is used, all intersections can be aligned. This is somewhat misleading, because the alignment is perfect only at a single point along the intersection. Therefore, there still can be misalignment at other points along the intersection, especially for an extended intersection. However, calculations show that the misalignment can be made small in some cases, making this an attractive approach

which simplifies fabrication. The application of this approach to the 2-D lens problem is possible, because the optical efficiency of a single hologram lens in a HUD array remains high for considerably larger horizontal angles than it does for vertical angles.

In the designs considered, the central column and each horizontal row are aligned with all misalignments occurring along the horizontal intersections between rows. This alignment procedure was chosen arbitrarily. By changing the alignment procedure, it is possible to distribute the misalignment so the local distortion is more uniformly distributed. This can be a useful technique for cases where the amount of distortion is small.

Use of curved source surfaces can reduce the variation of focal length across the array and thereby reduce the amount of local distortion. This technique is most useful in the horizontal dimension and would have to be used in conjunction with a reduced vertical off-axis angle.

Because resolution is not a first-order problem in these systems, the hologram construction point sources can be changed under the restriction that the same object/image relationships hold. This technique has been called a "warped" design, by which it is possible to modify the distortion properties of the elements while still maintaining a high optical efficiency. Considerable analytical work is required to determine the type of design modifications that decrease local distortion without losing efficiency. In general, these modifications will be directed toward reducing the changes in curvature and orientation of the array elements. The simplest effective modification is to change the location of the design pupil from that of the system pupil.

The selection of a hologram array design technique depends on interaction with the relay optics design work. The latter three techniques described above require modifications of the present design and the analysis computer programs. At the present time it is anticipated that a combination of a reduced off-axis angle and a warped design will reduce the local distortion within the allowable limit.

4.4.4 Analysis Techniques

The ray-tracing techniques used to analyze the distortion of images projected by arrays are briefly described below. The imaging problem is simplified by assuming that for the HUD system, the eye pupil limits the accepted ray bundle in such a manner that there is no resolution loss. This means that only the central ray of the bundle need be calculated, because this ray defines the direction of the image. On this assumption, the approach that has been adopted is to calculate and plot the images of a set of concentric squares on the object plane. This produces a graphic and easily interpreted display of the image size and distortion properties.

The procedure then is to define an array and to calculate the set of construction point-source locations that satisfy the array alignment criteria previously described. With these data, a set of concentric squares is produced on the source plane of the array, and for each of a set of 400 equally distributed points on each square, a location of the array is found that directs a ray from that point through the desired point in the pupil. The direction of this ray thus defines the direction of the image of that point, and the set of directions for the 400 points on each square defines the image of that square. An x-y plot of these data provides an image as an observer would view it. Qualitative and quantitative measurements then can be made to evaluate the image and thereby the array. By tracing rays through two points in the pupil, the amount of binocular disparity is measured.

4.5 Large Field of View HUD System Analysis

4.5.1 Introduction

This analysis is limited to flat-plate systems as limited by present analysis capability. However as previously discussed, it is possible to utilize a curved canopy as the array substrate. Indeed that configuration offers potential advantages in reducing distortion. In this analysis, both hologram array and single hologram systems are considered, and their

performance is compared. In particular, systems with a 60 degree horizontal FOV and a 45 degree vertical FOV are evaluated. The system designs were accomplished using the basic design techniques described in Section 4.4.

The basic geometry for the 60 x 45 degree FOV system is shown in Figure 4-22. The projected size of the input aperture is 34 inches horizontal by 26 inches vertical, for a 5-inch square viewing pupil and a pupil-input plane spacing of d = 25 inches. All systems described here require magnification of the liquid crystal source plane, which is assumed to be 3 x 4 inches. The locations of the aerial image planes for M = 3, 4-1/2, and 6 are shown in Figure 4-22 for $\phi = 30$ degrees (solid line). For $\phi = 50$ degrees the array position and the folded optical axis are shown by dashed lines. In Figure 4-22, the asymmetry angle ψ and the source plane rotation angle Ω are zero.

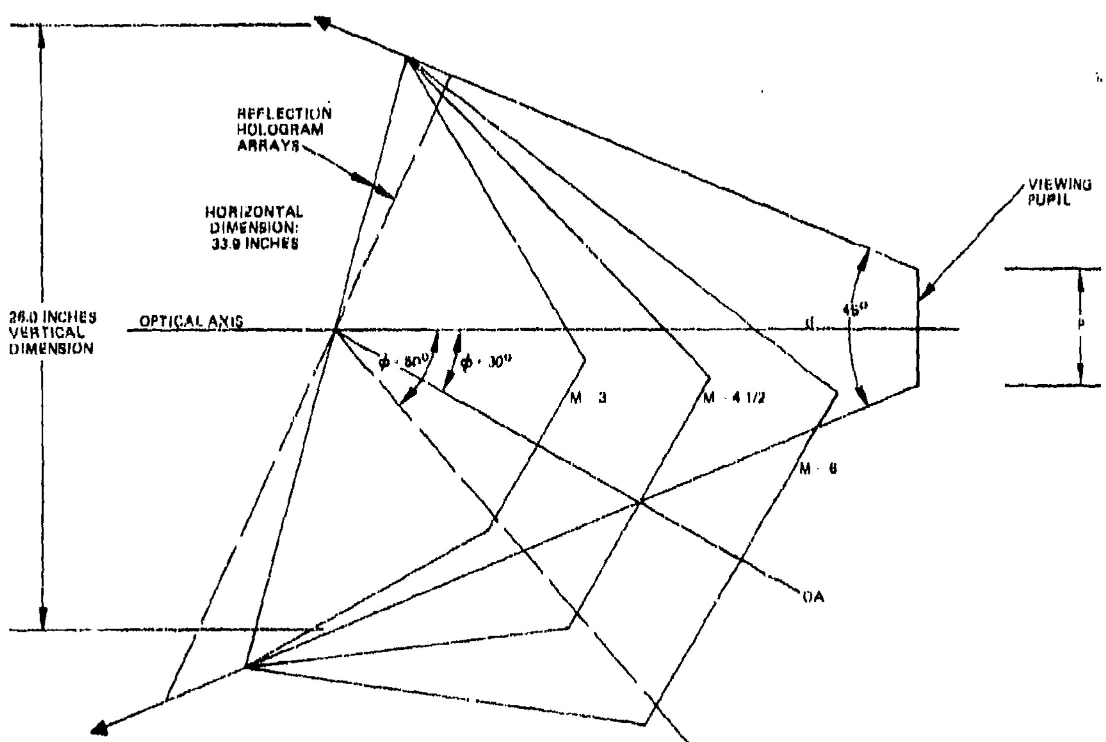


Figure 4-22. 60 x 45 degree field of view system.

These systems were studied by the ray tracing techniques described earlier. Figure 4-23 shows the viewing pupil plane and the points through which rays were traced to obtain the desired data. Pairs of points along the diagonal line were used to obtain maximum and average collimation errors as a function of pupil size. Normal binocular disparity data were obtained using the points indicated by solid triangles, centrally-located in the pupil. Maximum binocular disparity data were obtained using the solid circle points in the upper-left-hand corner of the pupil and the solid square points in the lower-right-hand corner of the pupil. All binocular disparity data were calculated using a standard interpupillary distance of 68 mm (2.67 inches). The input image in all cases was a rectangle having the same 60:45 ratio of width to height as the desired FOV. All angular error data were calculated by tracing rays from 400 points uniformly spread around the input rectangle through each point in the pupil. The directions of rays from corresponding points were compared for each of the 400 points, and the magnitude of the angular deviations were calculated. The maximum deviation and the average deviation for the 400 points provided the data for the analyses. X-Y plots of the ray directions for the 400 points and X-Y linear plots of the binocular disparity data for the 400 points aided in interpretation and verification of the data. (See Appendix C for examples of these plots.) The configuration for all these data is $\phi = 30$ degrees, $\psi = -10$ degrees, $\Omega = 4$ degrees. (See Figure C-1.)

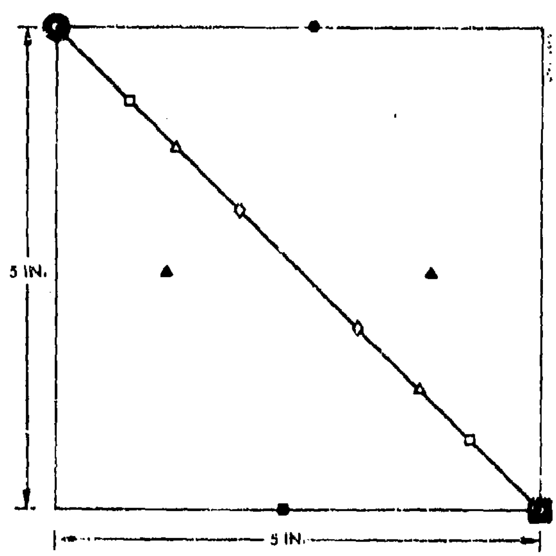


Figure 4-23. Viewing pupil plane.

4.5.2 Distortion

The X-Y plots of output ray directions were measured to determine the actual angular dimensions of the output image. The horizontal angular image size is plotted against the horizontal input image size in Figure 4-24 for a 5 x 11 array (5 elements horizontal x 11 elements vertical) and a single element system. It is apparent that the array image is considerably more linear than the single element image. The amount of distortion at the maximum field, relative to a linear display, is -3.6 percent for the array and -22.8 percent for the single element.

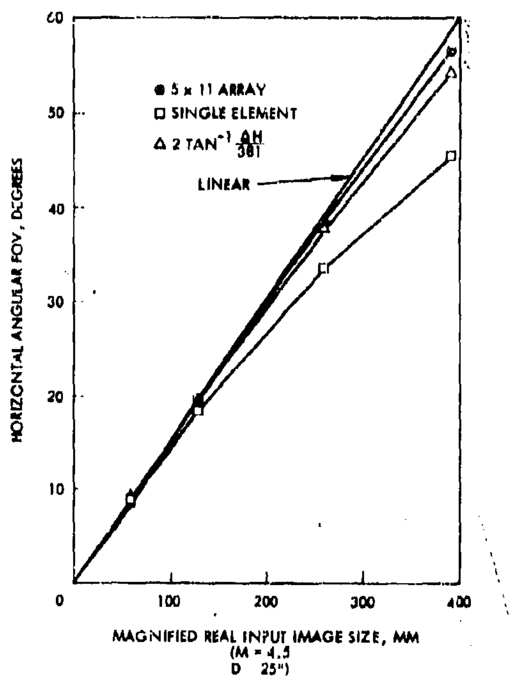


Figure 4-24. Displayed angular image size versus input image size.

The variation in vertical output image size is shown in Figure 4-25. The FOV ratio plotted is the output vertical-to-horizontal field ratio divided by the input image vertical-to-horizontal size ratio, which was constant to 0.75. The desired value of the FOV ratio is therefore 1.0. The vertical bars in Figure 4-25 show the amount of variation in the vertical size of the projected images. For a single element, this variation is due to global distortion. For the array, the variation is due to local distortion at the unaligned intersections of the array. Again, the advantages of the array are apparent — less than 5 percent distortion in the array image.

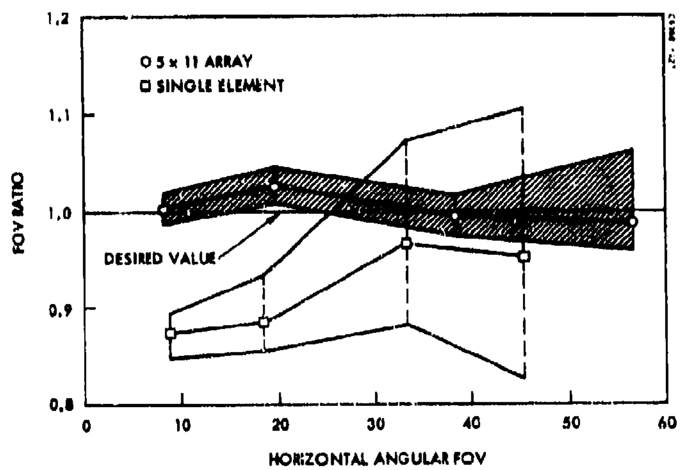


Figure 4-25. Variation in displayed image size.

4.5.3 Collimation Errors

Collimation errors are the variations in image location as the viewer's eye moves within the pupil are, remaining fixated on a single image point, as depicted in Figure 4-13. The magnitudes of these errors were calculated for each of the 400 points in the input image, and the maximum and average error magnitudes were recorded. These data were plotted against several system variables.

Figure 4-26 shows the average error for a 5 inch square pupil, a 3 inch square pupil, a 5 x 11 array, and a single element system as a

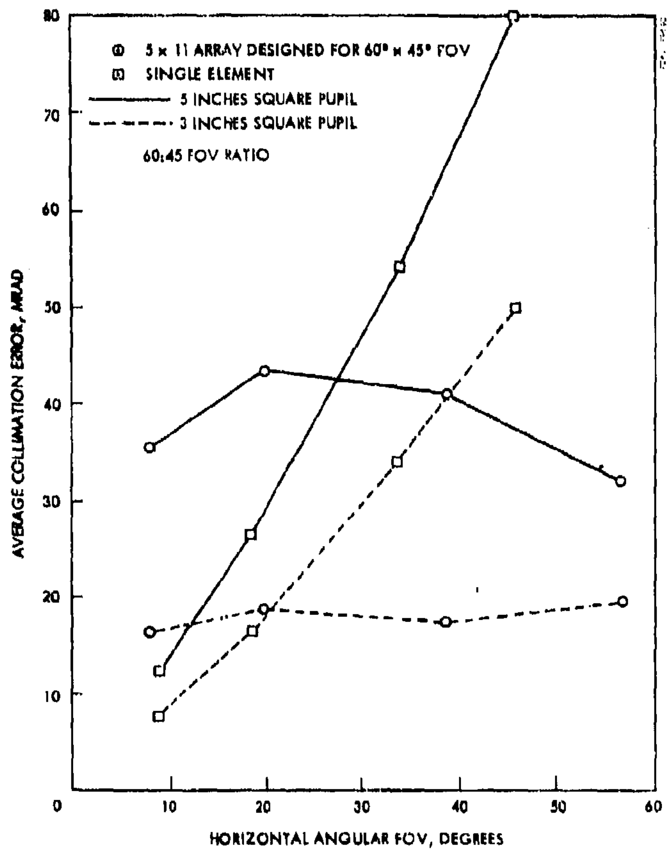


Figure 4-26. Collimation errors.

function of the horizontal size of the project image. The maximum collimation error (i.e., the worst error for the 400 points) is plotted in Figure 4-27 for the same cases. The array was designed for a 60 x 45 degree FOV. The behavior of these systems is as expected; the array errors are approximately constant as a function of FOV, while the single element errors increase rapidly. The ratio of errors at the edge of the field should be roughly constant. Thus for an array system designed for a 30 degree FOV, the average collimation error would be approximately 17 mrad of 1 degree. In other words, the average error for an array designed for a certain FOV should be approximately 1/3 the average error for the single element system at that FOV.

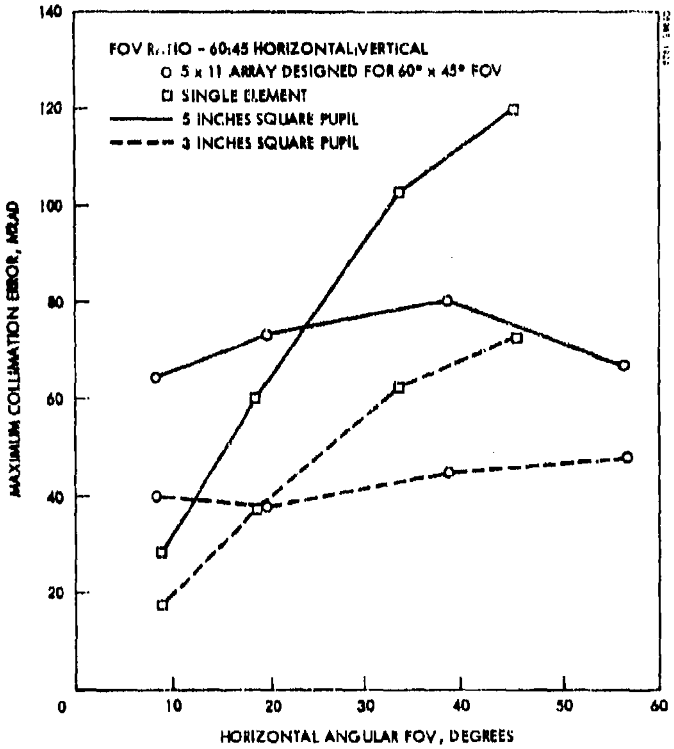


Figure 4-27. Collimation errors.

The collimation errors increase with the size of the viewing pupil, and this relationship is shown for a 5 x 5 array, a 5 x 21 array, and a single element in Figures 4-28, 4-29, and 4-30, respectively. The data points in these figures correspond to the selected pupil points shown in Figure 4-23. The "maximum" and "average" values refer to the 400 input points around a 4:3 rectangle covering approximately a ±30 x 22.5 degree FOV for the arrays and somewhat less for the single element. The curves are not markedly different for the different systems. The relatively large maximum errors at small pupil size for the 5 x 5 array are due to the relatively large local distortions present in this system. It is not surprising that the arrays give collimation errors of this magnitude, since they are designed on a "local" basis.

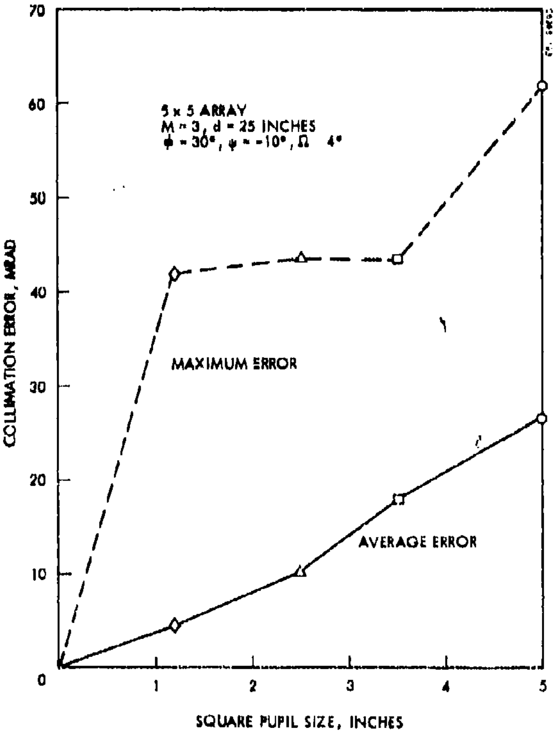


Figure 4-28. Collimation errors.

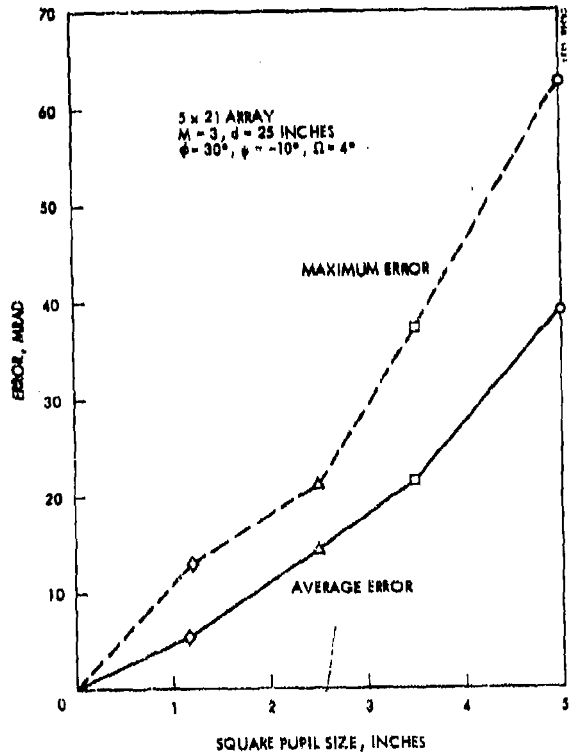


Figure 4-29. Collimation errors.

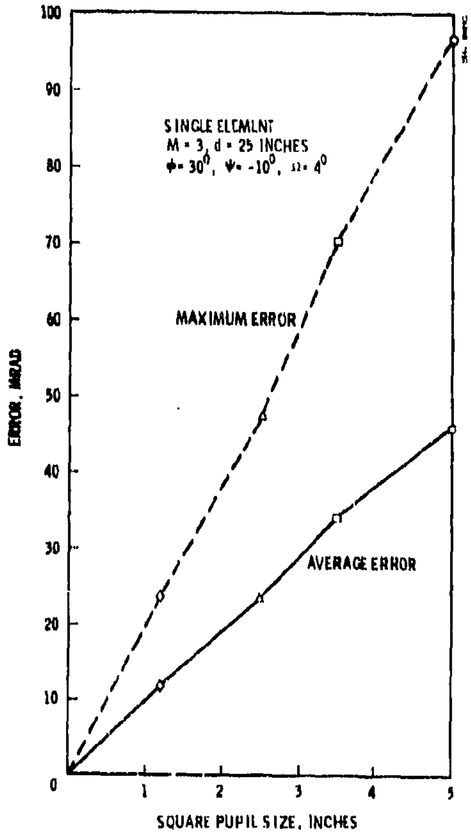


Figure 4-30. Collimation errors.

4.5.4 Binocular Disparity

The binocular disparity, or angular error between the viewer's eyes, should increase linearly with maximum field size. This must be checked by calculations. These errors are calculated for the solid triangle points of Figure 4-23. The maximum and average errors over the 400 input points are shown as functions of the FOV for a 5 x 11 array and a single element in Figure 4-31. These data are similar to the collimation errors previously discussed. Again, the average array binocular error is essentially constant over the FOV and should decrease with the maximum design FOV of the array. The maximum binocular error is dependent on the number of elements in the vertical (unaligned) direction as shown in Figure 4-32. This

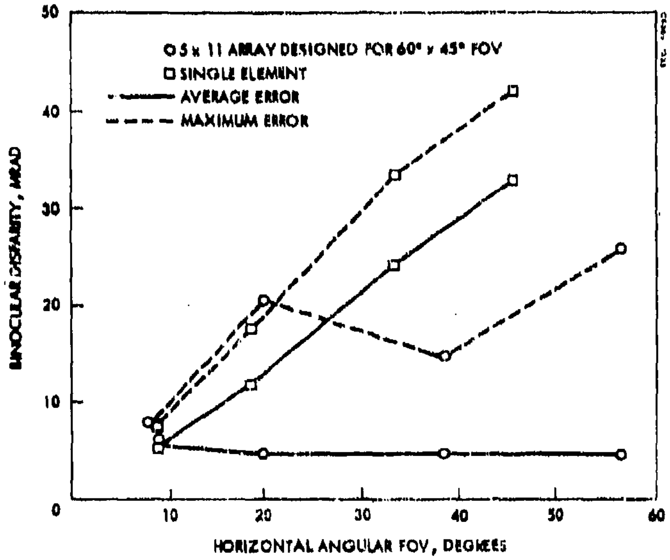


Figure 4-31. Binocular disparity errors.

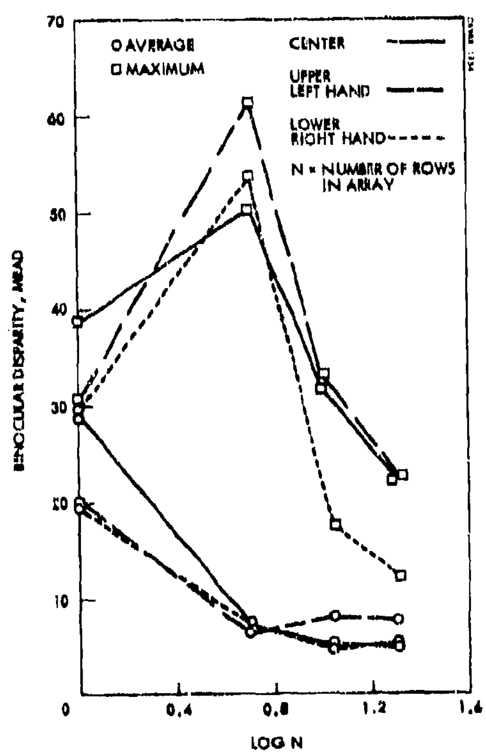


Figure 4-32. Binocular disparity errors.

indicates that improved design techniques will decrease the maximum binocular disparity for a given array, but probably will not have an appreciable effect on the average error. The effect of magnification on binocular disparity is shown in Figure 4-33, and the effect of variations in pupil-to-array spacing, d, is shown in Figure 4-34. There is not a strong variation in binocular disparity with these parameters.

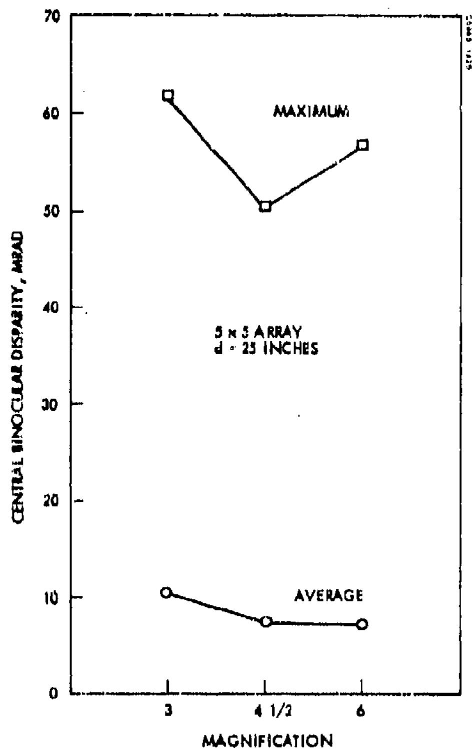


Figure 4-33. Effect of magnification on binocular disparity.

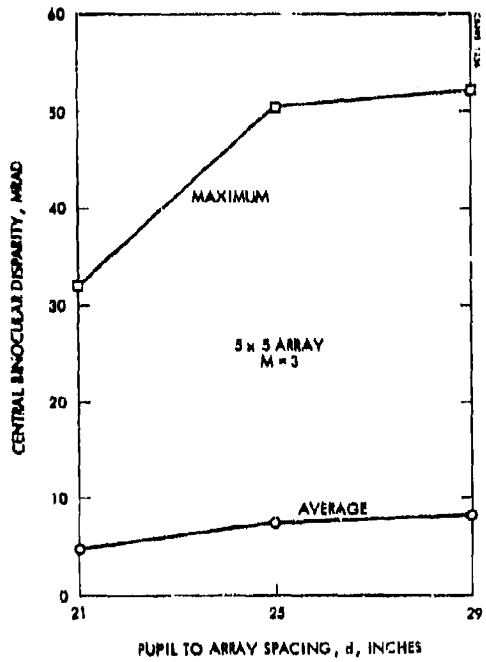


Figure 4-34. Effect of pupil to array spacing on binocular disparity.

4.5.5 Resolution

The resolution of the HUD using holographic lens/combiner is a function of two factors. These are off-axis aberration and chromatic dispersion.

Off-Axis Aberrations

For symmetric hologram optical elements, i.e., those with asymmetry angle $\psi = 0$, the following approximate expression for angular errors has been derived:

$$\Delta\theta \approx 80 \frac{D(D+P)}{fd} \text{ (mrad)} .$$

In this expression, $\Delta\theta$ is the maximum angular error in an image formed by a hologram optical element of dimension D through a pupil of size P. The hologram element focal length is f, and the spacing between the pupil and the element is d. For a typical HUD element, D = 100 mm, f = 300 mm and d = 600 mm. For the eye, P = 4 mm. These values give $\Delta\theta$ = 4.4 mrad, the accumulated error over the element. For resolution, however, D = P, giving $\Delta\theta$ = 0.014 mrad. Thus, there is no resolution loss due to the off-axis aberrations, but there is distortion from the accumulated error.

Chromatic Dispersion

For reflection holograms, an approximate expression for the angular resolution resulting from a source spectral bandwidth $\Delta\lambda$ is

$$\Delta\theta \approx \frac{\Delta\lambda}{\lambda} \sin\psi ,$$

where λ is the average wavelength, ψ is the asymmetry angle of the hologram, and $\Delta\theta$ is in radians. For λ = 5400Å, the spectral bandwidth for 1 mrad resolution is

$$\Delta\lambda \text{ (nm)} \approx \frac{30}{\psi\text{(degrees)}} .$$

Therefore, a hologram element with an asymmetry angle of 15 degrees would require a source spectral bandwidth of less than 2.0 nm to achieve a resolution of 1 mrad. This means that if the source of illumination is near the desired peak of visual response (5400Å), a bandwidth of 20Å must be maintained to provide the design goal resolution of 1 mrad.

4.6 Conclusions

4.6.1 System

Hologram Array Versus Single Element

For simplicity of design and ease of fabrication, it is desirable to use a single holographic optical element. However, the single element system demonstrates poor performance relative to the array. Optical efficiency, global distortion, collimation, and binocular accuracy are much worse in the single element systems. The disadvantages of the array systems are their complexity to design and build and the system errors are larger than desired for a large FOV, large pupil system. As the technology develops, the techniques will improve and both errors and cost will decrease.

Array Design

Present array designs are limited to flat plate configurations that utilize the basic alignment criterion. These configurations, particularly those with a small number of elements, show local distortions and discontinuities at the unaligned intersections between elements. Design techniques that are presently being implemented on a company funded program are directed toward solving these difficulties and developing curved substrates for the arrays. These new design techniques will be available for future work on the HUD application. Further design techniques will allow optimization of array and system parameters using binocular disparity, collimation errors, and/or local distortion as penalty functions.

Configuration

The flat plate configuration parameters ϕ, ψ, and Ω; along with the magnification, pupil-to-array spacing, FOV, and pupil size; define the array optical system with the present design techniques. With the other parameters fixed, the configuration angles have a strong effect on the image characteristics. The amount of overall distortion and the size of the local image defects increase roughly as $\sin \phi$. For a given off-axis angle ϕ, the

asymmetry angle ψ and the source plane rotation angle Ω can be varied to minimize the local image defects. The overall distortion is also dependent to some extent on ψ and Ω. The overall distortion is shown in Appendix C for several different configurations.

Curved Arrays

It is feasible to produce and use reflection hologram arrays on curved substrates, and this provides the possibility of using the aircraft canopy as the substrate for a HUD array. A proper choice of curvature can potentially greatly reduce the amount of overall and localized distortion in the image.

Relay Optics

For a large FOV and small source, magnification of the source and relay optics are required. For large viewing pupils, the relay optics have a low f/number. It is possible that the relay function can be provided by a holographic optical element, but detailed investigation of this was not possible in the present program.

The presence of the relay optics has one very beneficial effect on the system, i.e., the overall optical efficiency is greatly improved. This occurs because the low f/number relay element collects a large fraction of the light from any given source point and directs it through the viewing pupil area.

4.6.2 Resolution

Resolution loss in a holographic HUD system can come from two sources: off-axis aberrations and the source spectral bandwidth. For viewing with the eye, there is no resolution loss expected due to the off-axis aberrations. Chromatic dispersion increases as the sine of the asymmetry angle ψ and usually does require some limitation of the source spectral bandwidth in order to achieve the desired resolution. In order to provide 1 mrad resolution the BW must be held to approximately 20Å. Substrate curvature affects resolution only slightly in that the local asymmetry angle may be somewhat changed, thereby varying the amount of chromatic dispersion.

4.6.3 Distortion

For a given off-axis angle ϕ, the asymmetry angle ψ and the source plane rotation angle Ω can be adjusted to provide minimum overall distortion. In the basic design, the amount of residual local distortion is proportional to $\sin \phi$, and inversely proportional to the number of array elements in the vertical or unaligned direction. The residual distortion depends on other system parameters, particularly the relative size of the array focal length and the pupil-to-array spacing. For a 60 x 45 degree FOV, 5 x 11 array with ϕ = 30 degrees, ψ = -10 degrees, Ω = 4 degrees, d = 25 inches and f = 15 inches, distortion is less than 5 percent.

For a given system, residual distortion can be removed by adjusting the input image. For the array systems, this procedure does not alter the number of resolution elements available in the display. It may be possible to reduce distortion by optical techniques, using additional elements and/or stops as is done in optics technology.

4.6.4 Field of View

From the present studies, the apparent limitations on the display FOV are binocular disparity and pupil (collimation) errors. The former causes a difference in image direction for the two eyes of the viewer, and the latter causes apparent changes in image direction as the viewer's eye moves within the pupil area. Both errors are approximately constant with changes of FOV in a system designed for a particular maximum field of view. The binocular disparity errors vary with the maximum FOV as

$$\text{Binocular Disparity (mrad)} \approx \text{FOV (degrees)}/12 , \qquad (4\text{-}17)$$

and the pupil errors vary as

$$\text{Pupil Error (mrad)} \approx 2/3 \text{ FOV (degrees)}. \qquad (4\text{-}18)$$

Equations (4-17) and (4-18) should not be relied on for accuracy, since they result from plausible arguments rather than parametric studies. Also, these equations refer to a basic design procedure, and improved designs may show smaller errors.

To the extent that equations (4-17) and (4-18) are correct, they predict poor performance for large FOV systems with large viewing pupils. The particular system studied in detail (60 x 45 degree FOV) produced a worst case pupil error of about 2.3 degrees across the diagonal of a 5 inch square pupil, and a binocular disparity of 0.3 degree. Hopefully, with further analysis and an extended parametric study, improvements can be made. Improved designs are becoming available, and a parametric study is the first order of business in the future.

5.0 LIQUID CRYSTAL DISPLAY: TRADEOFFS AND ANALYSES

5.1 Introduction

A liquid crystal is the popular name for a material displaying some characteristics of a liquid (relatively low viscosity) and some characteristics of a crystal (molecular ordering). Normal reference to a liquid tacitly means reference to an isotropic liquid – one without molecular ordering or without a determinable orientation axis. Crystalline materials, on the other hand, are generally solids which exhibit definite structural forms (cubic, tetrahedronal) with definite molecular orientation: A liquid crystal material is one that exhibits a mesophase state between the solid and the isotropic liquid phases over a significant temperature range. The molecular order and hence the optical properties of these materials are influenced by electric fields and/or currents making them of interest to workers in the area of technology.

The discovery of the liquid crystal mseophase dates back to 1888 and was observed as a different "turbid liquid" phase occurring during the melting of a cholesterol compound. On cooling, the compound displayed a transition range where incident light was spectrally separated and reflected, exhibiting a behavior similar to a variable density reflective diffractive grating. Since the early discoveries, a number of researchers have identified many different compounds that exhibit this mesophase between the solid and the isotropic liquid phases. Liquid crystal materials have been divided into three classifications: cholesteric, nematic, and smectic, depending on the geometric order of the molecular structure.

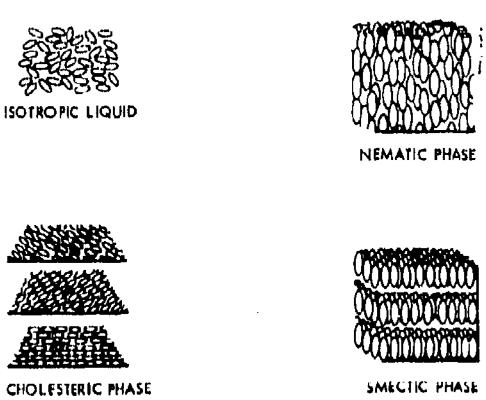
Transmissive and reflective cells are identified with the placement of the light source and the observer. A cell is transmissive if viewed from

the side opposite the light source. A cell is reflective if viewed from the same side as the light source, regardless of whether the cell is inherently reflective due to the liquid crystal material characteristics or whether an internal mirror or an external mirror is used. Therefore, a cell is reflective if it is used in that manner, and certain cells can be used either way if a partially reflective mirror is used.

In this section, a description of liquid crystal materials is presented. The electro-optic light modulation effects of interest are described and the material type and operating mode most suitable for the HUD development program is selected. Finally, a description of the construction of a completed display surface is presented. This includes the proposed physical assembly methods and a description of the large scale integration (LSI) interface electronics required to drive the display matrix.

5.2 Liquid Crystal Materials

Liquid crystal materials are composed of long rigid molecules of a wide variety of chemical compositions. These form regular, ordered orientations due to their physical structure and their effective electric dipole orientation. The molecular ordering of the three types of liquid crystals compared with the random orientation of an isotropic liquid is shown in Figure 5-1.



The molecular axes of isotropic liquids are randomly oriented. By contrast in the nematic phase, molecules all have their long axes parallel to each other, but are free to move in any direction. In the smectic phase, molecules exist in parallel layers and any two layers are free to slide over each other so long as the individual molecules do not move out of their layers. In the cholesteric phase, molecules lie parallel in layers with the alignment axis shifting in each successive layer so that a helix is traced out through the layers.

Figure 5-1. Liquid crystal molecular ordering.

5.2.1 Types of Molecular Order

In the isotropic liquid, there is no degree of molecular order. In the cholestric mesophase, the molecules are parallel within a thin plane, and the molecules in a plane are held at a particular degree of rotation (long axis) with respect to the molecules in the adjacent planes. The rotation of these molecules, observed as one passes along a line normal to the alignment planes and plots the molecular axis at each plane, can be described as a continuous twist or a helical form. If a sufficient number of planes are passed to arrive at a point where the molecules are parallel to those in the first plane, the distance can be identified as the period of the helix. This period is within (or close to) the wavelength of visible light for materials of interest. The optical effects of this pattern and the effects of electric fields on the pattern are discussed below. In the nematic mesophase, the molecules are ordered to the extent that the long axes are parallel. In the smectic mesophase, the molecules are all parallel and are further restricted to discrete planes normal to the long molecular axis. The smectic mesophase is of the least interest for controllable optical qualities and will not be discussed further.

All liquid crystal materials that exhibit electro-optical properties have molecules with electric dipole moments. The material is said to exhibit positive dielectric anisotropy if the major component of the dipole is parallel to the long axis of the molecule, and to exhibit negative anisotropy if the major component is perpendicular to the molecular axis.

5.2.2 Electro-Optical Effects from Dynamic Scattering

The application of an electric field across the liquid crystal film reorients the molecular axis and aligns the dipole axis with the electric field. In the nematic materials, the reorientation has the effect of forming small domains of molecules where the molecular axes are parallel. From one domain to another, there are variations in the alignment due to the rotational position of the molecule (about its major axis) and subsequent variations in the dipole position before application of the electric field. The anisotropy of the liquid crystal material causes local variations in the index of refraction between these domains which form in volumes with dimensions of a few

microns. In some applications, the field effect of the local rotation of the molecule achieves the desired optical results by modulation of light refraction or polarization qualities. In the majority of current applications, a secondary effect is created as follows. If the electric field is greater than some threshold critical field, ionic current flow takes place, and the domains are moved by the physical interference and the interaction of the field associated with the ions in motion. This effect is called hydrodynamic turbulence. As light is projected through material in this turbulent state, it is scattered by the multiple refractions at the domain boundaries. It is important to note that this scattering is proportional to the current through the material; consequently, this mode of operation is suitable for the presentation of a range of gray shades for the display of sensor video. An indication of the light modulation properties of one particular Hughes liquid crystal formulation is presented in Figure 5-2. This family of curves indicates that the

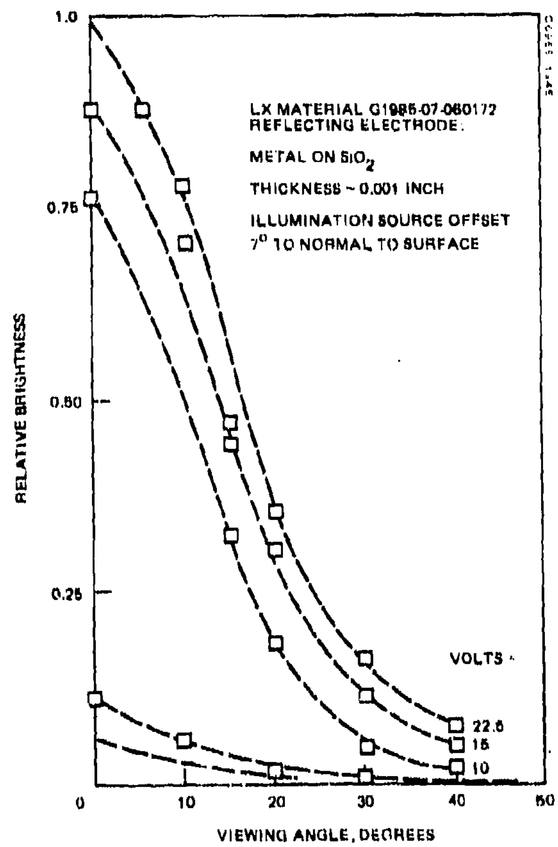


Figure 5-2. Liquid crystal display intensity modulation.

cell has a background luminance of approximately 8 (arbitrary units, since the cell merely scatters a portion of the incident light under excitation), and a monotonically increasing brightness with applied voltage at all viewing angles. The actual gray shade rendition is a function of the contrast requirement and incident light. This is discussed further in the baseline design section of this report.

In cholesteric materials, the reorientation has the effect of modifying the helical pitch of the planes of molecules. Depending on the original orientation of the helix and the relative direction of the electric field vector, the helix may be stretched or compressed, or the structure may undergo a phase transformation, i.e., to a nematic or an isotropic phase. The original conditions are controllable and repeatable.

5.2.3 Electro-Optical Effects from Field Effects

A field effect device, as opposed to a dynamic scattering device, is one that uses the realignment of the molecules and the resultant change in optical transmission for information display. One factor is common to all field effect displays. The liquid crystal material must be of much higher purity to reduce any current flow and subsequent turbulence causing dynamic scattering. The bulk resistivities of the field effect material and of the dynamic scattering material are approximately 10^{13} ohm-cm and 10^{10} ohm-cm, respectively. A typical nematic field effect device is fabricated by mechanically polishing the transparent conductive coatings used for the electrical contacts unidirectionally. A liquid crystal material with positive dielectric anisotropy is used, and the molecules will align themselves with the abrasion marks left by polishing these surfaces. The cell is assembled with these abrasion marks orthogonal to one another, causing the molecules to form a 90 degree helix in the direction normal to the surface (corresponding to the stable state of the liquid crystal material in the cell). This cell is placed between two parallel polarizing filters. In operation, incident light is polarized by one filter, rotated 90 degrees by the liquid crystal cell, and absorbed by the second polarizer. An electric field applied to the liquid crystal cell causes the molecules to rotate such that the major axis is

perpendicular to the surface. Since this causes the helix to disappear, the light is no longer rotated and is transmitted through the second polarizer. The applied field thus modulates the degree of rotation of polarized light through the cell. This field effect cell has the disadvantage that it must be a transmissive cell, since a reflection on the back surface would simply cause the light to be rotated through the liquid crystal again.

A similar device can be fabricated for a reflective system as follows. The conductive coatings are etched and treated such that a liquid crystal material with negative dielectric anisotropy can be placed in the cell, and the molecules will be oriented perpendicular to the surface. The lower surface is a reflector, and the upper surface is covered by a circular polarizer. In this case, an applied field rotates the molecules away from the optic axis. The birefringence of the crystal causes the linearly polarized light to become elliptically polarized, and light is reflected through the cell where it was blocked in the absence of an electric field. In general, the transition in these devices is fairly abrupt, making it difficult to control gray scales, and in the case of the reflective cell, the circular polarizer is wavelength sensitive.

Cholesteric materials can be used in transmissive or reflective cells and are normally used in the field effect mode. The basic mechanism of the electro-optic effect has been described as a modification of the helix pitch of the material. A cell may be constructed such that light incident at the Bragg angle is reflected with the angle of reflection a function of the helix pitch and consequently the applied field. The reflection is wavelength sensitive, but this does not represent a problem since the HUD illumination spectrum is limited to a 20Å bandwidth. Utilization of this type of cell for pictorial (gray scale) information requires the positional control of the exit cone of light and allows the exit pupil to be completely or partially filled by that exit cone. Slightly different preparation of the cell causes the liquid crystal to orient differently in the relaxed states, and the cell can be used as a transmissive device.

One known problem area is the temperature sensitivity of the helix pitch. Although certain materials are less sensitive than others, in general the temperature cannot vary more than a few degrees without passing through

the same range as that intended for the control range. Control functions can be included for temperature control of the display or for a bias voltage to counteract the temperature effects.

5.2.4 Electro-Optical Effect Trade-Offs

The majority of research in liquid crystal applications has been aimed toward digital displays, i.e., without gray scale content. Those studies relating to pictorial displays have been centered on the dynamic scattering mode of operation of nematic liquid crystals. The choice of a material for the HUD baseline system is the nematic liquid crystal because of its more advanced research state. Table V-1 shows a summary of three cell designs and a condensed of operating conditions. At this time, the field effect cells have not been sufficiently researched to consider for the baseline design. However, the potential advantages of faster operating speeds and lower drive voltage make them potential candidates for an improved design at a later date.

TABLE V-1. LIQUID CRYSTAL COMPARISON CHART

TYPE OF LIQUID CRYSTAL	MECHANISM OF LIGHT MODULATION	LIGHTING REQUIRED	ADDITIONAL OPTICAL ELEMENTS REQUIRED	DEVELOPMENT STATUS	COMMENTS POTENTIAL ADVANCEMENTS
NEMATIC DYNAMIC SCATTERING	HYDRODYNAMIC TURBULENCE	HIGHLY COLLIMATED	APERTURE AND FIELD LENS	MOST ADVANCED	BASELINE SYSTEM
NEMATIC FIELD EFFECT	POLARIZATION ROTATION OR DEPOLARIZATION	DIFFUSED AND POLARIZED	POLARIZER	INTERMEDIATE	FASTER SWITCHING SPEED. LOWER DRIVE VOLTAGE
CHOLESTERIC FIELD EFFECT	BRAGG EFFECT INTERFERENCE	SLIGHTLY COLLIMATED	DIFFUSER POSSIBLE	MOST RESEARCH REQUIRED	FASTER SWITCHING SPEED. INTERMEDIATE DRIVE VOLTAGE. HIGHER OPTICAL EFFICIENCY

The reflective cell is chosen for the baseline system as a result of the display element circuitry required. The circuitry developed to date has been formed in bulk silicon, which is opaque to visible light. Consequently, a reflective surface is deposited on the silicon surface to form the reflective

cell. Further developments in silicon-on-sapphire (SOS) circuitry will allow the use of transmissive cell designs. Since the operation of SOS circuits generally meet or exceed the performance of MOS circuits on bulk silicon, a simple transition is anticipated in evaluating the SOS technology.

5.3 Liquid Crystal Temperature Considerations

The liquid crystal mesophase of interest exists as a stable transition state, existing between the cool solid state and the warm isotropic liquid state. The operating temperature of a display device must lie within the bounds of the mesophase temperature extremes. There are no problems in satisfying a particular set of design specifications due to the increasing number of materials available and the wide range of associated mesophase temperature ranges.

5.3.1 Temperature Range Extension Through Material Formulation

Since it is advantageous to utilize a material with low viscosity in order to achieve faster excitation and decay rates and viscosity generally decreases with increasing temperature, a high mesophase range may be desirable. In this case, heating the display may be necessary and a cursory presentation of the required heating power will be given in this section. In the work performed by Bonne and Cummings it was found that a mesophase temperature range of -54°C to +71°C can be achieved by forming a eutectic mixture of several liquid crystals materials with the desired characteristics. Figure 5-3 shows a simple phase diagram of the MBBA and EBBA liquid crystal mixture. It can be seen that the pure MBBA material has a mesophase between 22° and 45°C, and the EBBA has a range between 38° and 77°C. The eutectic mixture is formed with 60 percent MBBA and 40 percent EBBA, and the resulting mesophase temperature range is extended from -10°C to +55°C for a total range of 65°C. The temperature range is extended further to 95 percent (-35 to +60 degrees) by including APAPA in a ternary eutectic mixture. Several reported compounds and eutectic mixtures exhibit nematic mesophases that extend above 100°C. This is important, since the materials used at present exhibit viscosities leading to rise times and decay times higher than that desired for a television format presentation. Decay time ranges from 100 to 1000 milliseconds at

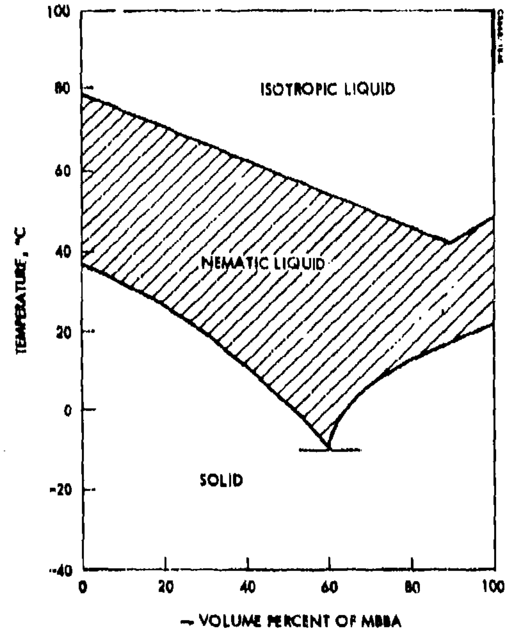


Figure 5-3. MBBA phase diagram.

room temperature for the majority of the materials available at present. Figure 5-4 shows the rise time of the materials studied by Bonne and Cummings as a function of temperature. A statistical analysis of the viscosity of referenced liquid crystal materials indicates that a significant deviation from the rise time characteristics shown is unlikely unless a new family of liquid crystal materials is observed.

5.3.2 Temperature Range Extension by Heating

Use of the presently available materials is satisfactory if the display can be heated to improve the total response time. Figure 5-5 shows both the rise and the fall time as a function of temperature and includes a correction function for variations in rise time as a function of applied voltage. The results plotted were performed with a 40 volt pulse on a 0.5 mil thick liquid crystal layer; the analog video voltages applied to the Hughes display will range from approximately 5 to 25 volts to exhibit the full gray scale range. With an applied voltage of 20 volts, the rise time and fall time are essentially equal to 200 milliseconds at 25°C and 20 milliseconds at 71°C, which

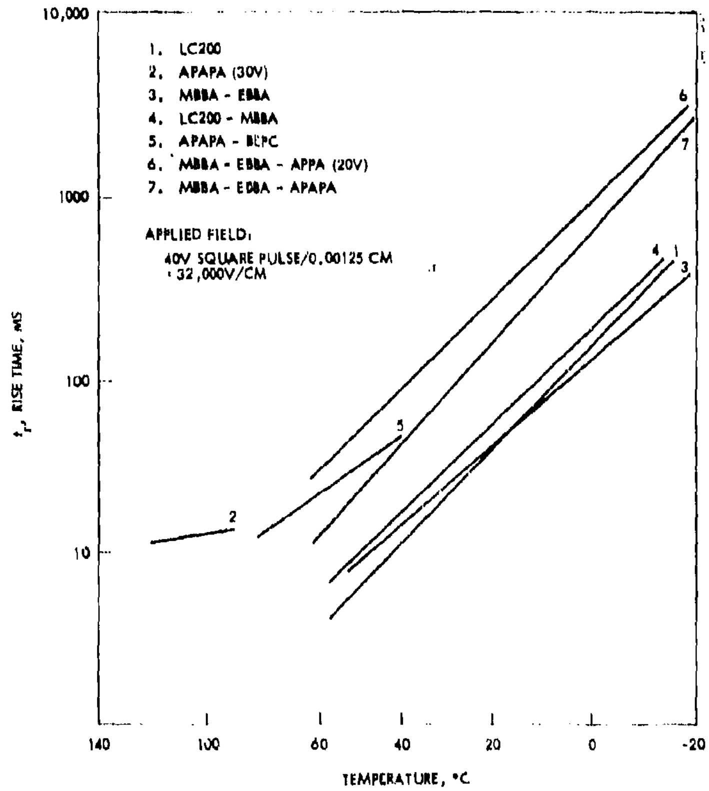


Figure 5-4. Rise time versus temperature for all nematic liquid crystal systems studied.

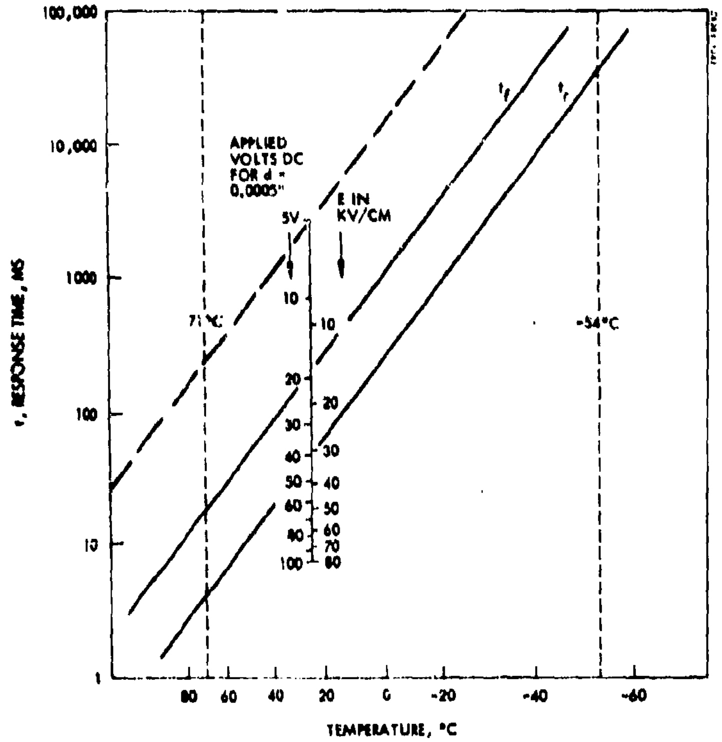


Figure 5-5. Average response times versus temperature for applied E-field pulses of 32 kv/cm.

is adequate for a 30 frame per second television format presentation. The display can be heated with a sheet or wire resistance element imbedded in the epoxy band between the substrate and the silicon display wafer. Assuming that the cockpit ambient temperature is approximately 25°C, the display would have to be heated to 50°C above ambient.

A preliminary study was performed to determine the feasibility of heating the panel. It was assumed that the rear of the panel is well insulated and that forced air circulation was not present across the face of the display. Under these circumstances, the majority of the cooling takes place by air conduction cooling from the front 10-inch square surface and has been calculated to be approximately 0.4 watt per degree differential temperature. This figure is dependent on the ambient air circulation and could triple in value if a mild ambient air circulation passes over the display surface. These figures indicate 20 to 50 watts are required to heat the panel to 50°C above the ambient temperature.

5.3.3 Summary of Liquid Crystal Temperature Considerations

It may be said that existing technology provides satisfactory liquid crystal materials to meet the requirements of the display surface. The full temperature range can be met with eutectic mixtures of existing materials, but the materials should be heated during operation to lower the viscosity and improve transient response. This heating is practical, since preliminary analysis indicates that 20 to 50 watts of heating power is required. The illumination source required for the HUD application may provide heating of approximately this magnitude. This approach is pessimistic in that it assumes that new materials will not be developed to improve the display operation within the required time period, whereas new materials are developed almost monthly in this rapidly advancing field.

5.4 Electrical Operation of Display

5.4.1 Introduction

The purpose of the display electronics is to control the potential on each liquid crystal cell electrode so that the potential of each and, hence, the brightness of the display at the location of that electrode corresponds to the intensity commanded by the sensor at that point in the scene being presented. The electronics must provide the addressing and multiplexing functions required for the liquid crystal array, using circuits that can be fabricated economically and reliably in the required quantities and available space.

In conventional television systems, one video channel carries all the pictorial information in a serial analog data format. The camera (sensor) scans the scene from the upper left-hand corner along the top horizontal line of the frame, and then retraces and scans a second horizontal line from left-to-right. One scan from top to bottom of the picture area is defined as one field. A second field is then drawn beginning at the upper left-hand corner and the second set of lines are interlaced between the previously drawn lines. Together these two fields form an interlaced frame of the pictorial information.

Relating this format to the liquid crystal scan format, a serial line of television video data must be converted to a parallel data output format for simultaneous presentation to a row of liquid crystal picture elements.

In order to provide a display with 1-mrad resolution over a 45 x 60 degree field of view, the matrix display must contain approximately 750 x 1000 picture elements. For the use of binary logic, an array of 768 vertical by 1024 horizontal picture elements is recommended. At a 30 Hz focus rate, the active line period is 40 μsec.

5.4.2 Element Addressing Circuits

The schematic diagram in Figure 5-6 shows that each picture element is composed of three parts: a typical element liquid crystal cell, which is characterized by a small capacitance and a high leakage resistance, a field effect-transistor (FET), and a monolythic capacitor. Together, these parts constitute an elemental sample and hold circuit to stretch the 40 microsecond addressing pulses to the millisecond lengths needed to energize the liquid crystal material.

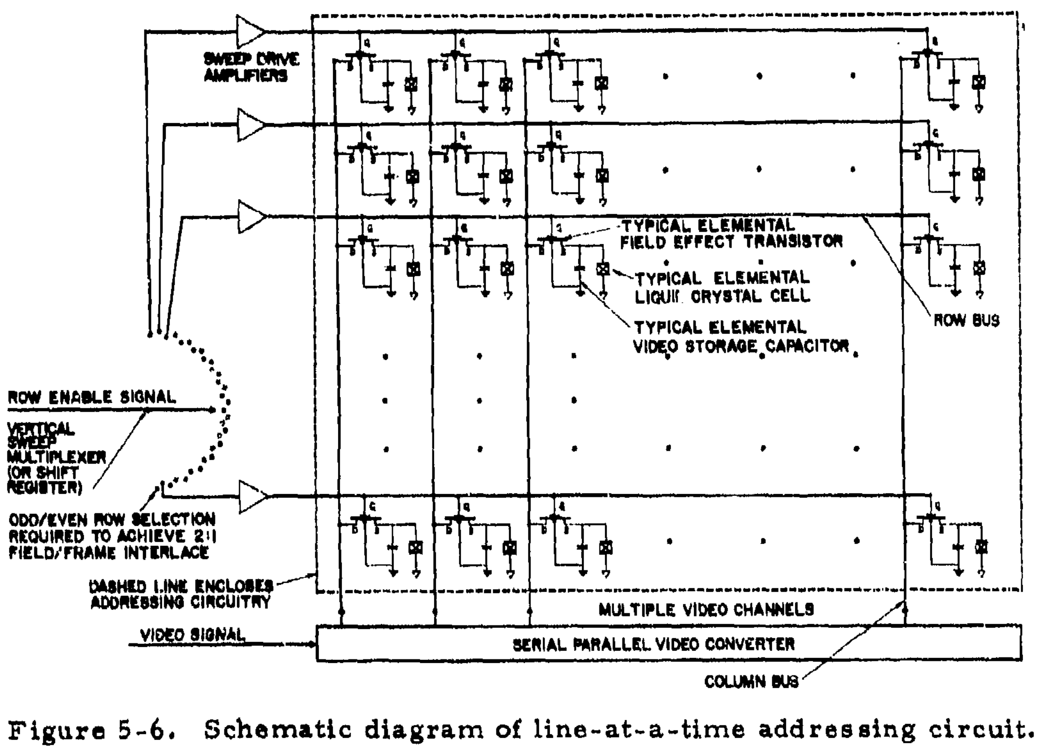


Figure 5-6. Schematic diagram of line-at-a-time addressing circuit.

Each FET is of the correct polarity (p-channel) and is connected so that when the gate is driven negative, the FET is turned on and the elemental capacitor is connected to its corresponding column electrode bus. Conversely, when the gate drive is removed (the gate voltage returns to zero or becomes positive), all elemental capacitors in the corresponding row are disconnected from the column bus lines by the high FET off resistance. In this manner, each of the elemental capacitors in any column is separated from the other capacitors in that column. Because the gates of all the FETs in any row are connected by the gate-electrode bus, an enable signal on any gate-electrode bus causes all the elemental storage capacitors in that row to be charged to the video level that is present on the corresponding column-electrode buses.

The circuit required to perform the sequential scan of the gate-row-electrode busses consists of a multiplexer or a serial-input/parallel-output shift register and a driver for each line of the display. One bit in the shift register corresponds to the address of one row (gate bus), and a single one in a field of zeros is shifted through the shift register to scan each field. When a 768-line display is being refreshed 30 times per second, the basic clock rate of the shift register is 768 x 30, or approximately 23 kilohertz. This rate is more than two orders of magnitude below the state-of-the-art for LSI-fabricated shift registers.

For the current configuration of the Hughes liquid crystal display, which uses the dynamic scattering mode of the liquid crystal material, the video signal must be approximately 20 volts to excite the liquid crystal to its maximum scattering condition (maximum brightness). The threshold voltage of the FET designs on the liquid crystal wafer is 4 volts, resulting in a gate voltage drive requirement of 24 volts. Because the output voltage level of the row select shift register is 3 to 4 volts, a buffer amplifier is required to provide the load isolation and the voltage gain. The amplifier must have the 24-volt output voltage swing with sufficiently high gain-bandwidth product and power drive capability to provide a good line drive pulse. Deterioration of this pulse shape causes smearing of the imagery between two adjacent vertical elements, because one row gate is not completely off before the succeeding row gate begins to turn on. One such

amplifier is shown in Figure 5-7. This amplifier has a slew rate of approximately 10 volts per microsecond when loaded with the characteristic row bus capacitance of 300 picofarads. This design will provide a satisfactory switching time, since the total desired pulse width is 40 microseconds.

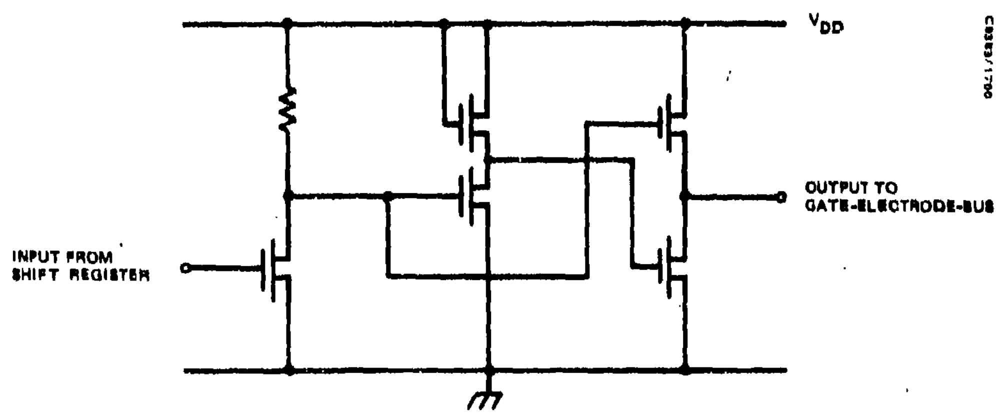


Figure 5-7. Schematic diagram of sweep driver amplifier.

At the time when a gate pulse addresses a given display row bus line, the video voltage corresponding to each picture element on that line must be present on each appropriate column bus line. A set of 1024 sample and hold circuits is required to convert the serial video signal corresponding to one line of information to 1024 output lines (horizontal elements). Figure 5-8 shows a typical schematic section of sample and hold circuits driven by a shift register corresponding to one line scan. Two identical circuits are used in order that one circuit can drive the display as the other is storing the succeeding line of video. The latch control bus line switches either set of holding capacitors to provide the input to the driver amplifier and subsequently the output data.

5.4.3 Conclusion

All of the devices described are within the current state-of-the-art of LSI semiconductor processing and packaging technology. Since the entire drive circuit can be fabricated using LSI techniques, the small area required allows the additional benefit of full circuit redundancy to insure high reliability

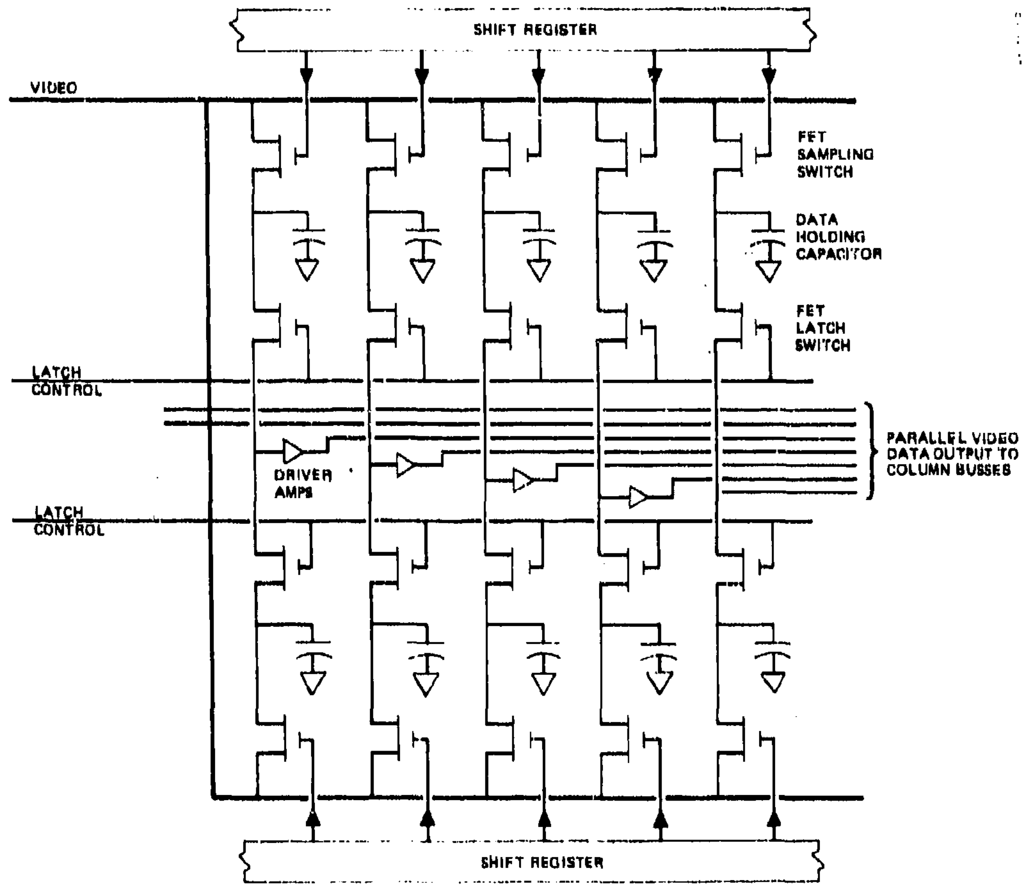


Figure 5-8. Typical serial/parallel video converter.

operation. The assembly is easily organized, sinxe the address bus lines extend across the entire array. Identical address circuits are placed on each side of the array and drive the bus lines simultaneously. In the event of a component failure after the display has been in operation for some time, the corresponding display bus line is addressed from one end only. The drive power of one FET output device is capable of supplying the required current for the display bus. The failure of one set of driver electronics will therefore be random and unrelated to any failures in the opposite set, and the probability of failure of the corresponding drive element on each end of a display bus is extremely low.

5.5 Physical Construction of the Display

The basic design concept of the Hughes pictorial liquid crystal display is not original, having been described by Lechner, et al, in 1970. What is unique and proprietary to Hughes is the way the liquid crystal display technology has been combined with the large-scale-integrated semiconductor circuit technology to yield a device that is physically realizable, using current state-of-the-art techniques. No new inventions are required.

The design is based on a sandwich structure of a thin layer of liquid crystal material between a transparent conductive cover glass and an assembly of interconnected semiconductor chips that have been previously mounted on a supporting substrate to ensure mechanical rigidity, uniform spacing, and surface flatness. Figure 5-9 illustrates the main components of the display structure. The following paragraphs describe how each layer in the structure is fabricated.

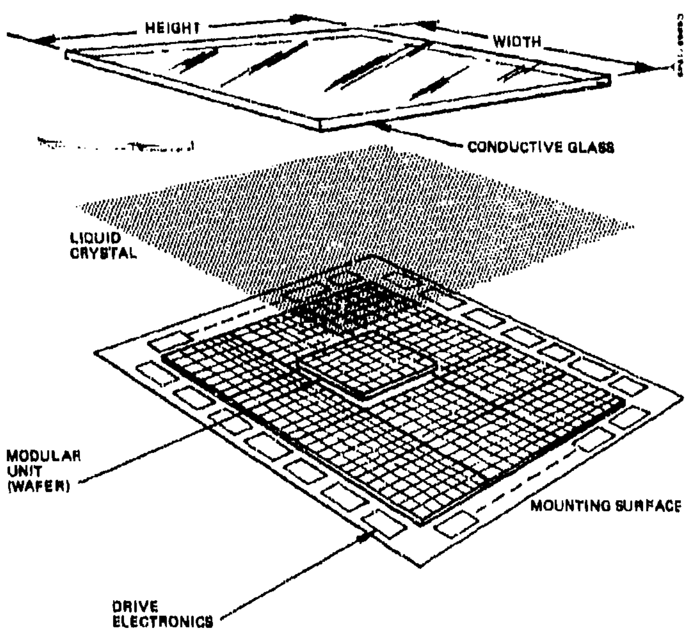


Figure 5-9. Building block approach.

5.5.1 Semiconductor Layer

The fabrication of the individual semiconductor chips, their mounting, and their subsequent electrical interconnection to form the back layer of the display structure represent the major portion of the display construction task. The resulting assembly of interconnected semiconductor chips provides the array of optically reflective electrodes, the circuits required to address each of the elements without introducing crosstalk, and the drive electronics required to convert the standard video signals to the signal level and impedance required for the display.

5.5.2 Semiconductor Chips

The electrode array module chip is a square semiconductor chip. The surface contains an array of metallic reflective electrodes. The top surface contains the transistor circuits and interconnections to perform the addressing function. The size of the electrode array module is limited by wafer processing size considerations and yield tradeoff studies. The larger wafer size requires fewer interconnections but the yield is lower. Current yield studies indicate that the optimum module size and element density for the HUD application is approximately 1 inch square with 256 x 256 elements. The display is made up of 12 such electrode-array chip modules in a 3 inch by 4 inch array to form the 768 x 1024 element resolution display. Due to the optical system tradeoff discussed in Section 4.2.2, the larger display size (6 inch by 8 inch) is more desirable from a system standpoint. As chip yield is dependent primarily on the number of elements per chip and not the density of elements on the chip, (within the density ranges under discussion), the element density is selected on the basis of optical design considerations. A six inch by eight inch display with 128 elements/inch has therefore been chosen for the baseline system design. The important features of the baseline design for the electrode array chip module are 1) the visual electrode occupies most of the single picture element area, because the FET requires only a small portion of the total area, 2) the FET can be fabricated with an OFF/ON resistance ratio of greater than 10^5:1, and 3) a separate capacitor, whose capacitance is large in comparison with the self capacitance of the liquid crystal elements cell, can be formed for each cell.

Preliminary design of the MOS circuits for the serial/parallel video converter and the row addressing indicate that the chips will be small enough to fabricate and mount on a substrate. Fourteen chips are required for these two major functions. The double redundancy requires that the 28 chips be mounted along each edge of the display area for a total of 40 circuit chips.

5.5.3 Chip Mounting

The semiconductor chips are mounted to a rigid supporting surface using an epoxy-type material. The drive module chips are positioned around the electronic array module wafers as shown in Figure 5-9. Flatness is maintained by assembling the semiconductor layer upside down on top of an optically flat surface, using the epoxy-type material to make up for the slight variations in chip thickness. Uniform spacing is maintained by using a precision saw for cutting the wafers to the required size with a tolerance of plus or minus 0.001 inch and by selecting the order in which the wafers are placed in the assembly (if necessary) to minimize tolerance buildup. This assembly process provides physical integrity to the 80 individual semiconductor chips and insures the flatness of the electrode surface.

5.5.4 Interconnection of Chips

Interconnections of chips is achieved by a selective metal vapor deposition process. The electrode array at the edges of the electrode array module chips are modified to permit an alignment tolerance of plus or minus 0.001 inch in the deposition of the metallic bridges. The last step in the deposition process is the addition of an insulator to prevent the electrode-busses and the electrode-bus bridges from acting as electrodes and forming scattering centers.

5.5.5 Transparent Electrode

The baseline design calls for the transparent electrode to be formed by the vapor deposition of indium oxide on glass. Indium oxide has the characteristics of high optical transmission, low electrical resistance, and electro-chemical stability in the presence of liquid crystal materials. The glass sheet covers the entire semiconductor layer, and a hermetic seal

is provided at the edge. An anti-reflect coating is applied to the front surface of the glass plate in order to reduce the specular reflections in the areas where the liquid crystal is diffusing the refracted light. This is necessary to realize the high contrast inherent in the display medium.

5.5.6 Liquid Crystal Material

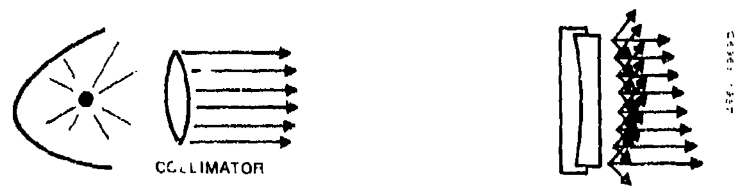
The thin layer of liquid crystal material sandwiched between the transparent conductive sheet and the semiconductor reflective layer exhibits the electro-optical phenomenon that generates the image. The baseline design calls for the use of an ester-type liquid crystal material. This choice may be changed as new liquid crystal materials are developed. The liquid crystal layer is achieved by sealing the display (except for the fill and evacuation ports), evacuating the voids, and then backfilling the display with liquid crystal material. The internal pressure remains lower than ambient, which is necessary to hold the transparent glass conductive sheet firmly against the spacers on the semiconductor layer for uniform cell spacing.

The baseline design does not call for a means for replacing the liquid crystal material, although it is certainly feasible. The task of refilling the display with new liquid crystal material is comparable to the task involved currently in regunning a cathode ray tube.

6.0 ILLUMINATION SOURCE; TRADEOFF AND ANALYSES

6.1 Introduction

The liquid crystal display is a light modulator. Incident illumination is scattered from the display surface as a function of the electric signal applied to the liquid crystal cell. The head-up display system (HUD), therefore, requires a light source to illuminate the liquid crystal, thus generating the imagery for the holographic lens. The variable light output from each point on the liquid crystal forms the visual object that is imaged by the holographic lens. This image, shown at infinity, is seen projected into the external scene by the use of the holographic lens/combiner. The conditions imposed upon the light source by the system are high brightness, narrow spectral bandwidth, and high efficiency. The degree of collimation of the light source will depend on the choice of the liquid crystal design parameters. These requirements originate from the operational constraint that the HUD symbology by viewable against an outside view of high ambient brightness without excessive attenuation or color change. The narrow spectral bandwidth is necessary to maintain high resolution on the holographic combiner. In general, collimation is required of a point light source if a dynamic scattering liquid crystal cell is used. The source may be a large area diffused source if a transparent liquid crystal cell with better separation of the light signal output to the unwanted background light is used. The reason for this is that in the scattering cell, an external aperture must be used for this separation, and the specularly reflected (or transmitted) light rays must converge to this aperture. These two alternate light source configurations are shown in Figure 6-1.



a. POINT SOURCE

b. DIFFUSE SOURCE

Figure 6-1. Alternate light source configuration.

6.2 Requirements

Operation of the HUD depends on the optical mixing of symbology and pictorial information with the view of the outside world. One of the foremost requirements of an advanced HUD is that the outside world view must not be distorted. Distortion includes both geometric and spectral distortion. In Section 4.0, the use of a multiple element holographic lens combiner to minimize distortion was discussed. With the holographic combiner, transmission of the illumination from the outside world is very high across the visible spectrum, except for the very narrow (20Å) band corresponding to the spectral band of the HUD symbology. This narrow band is necessary to insure high resolution projection on the hologram array. This narrow rejection band also results in little loss in illumination and very little color change in looking through the holographic combiner lens. An understanding of this advantage is obtained by analyzing the chromaticity diagram shown in Figure 6-2. The CIE chromaticity chart represents all hues and saturations of the visible spectrum plotted at equal luminosity. Any point on the perimeter of the curve represents a pure spectral color (monochromatic radiation) of unit luminance intensity. The resultant color of any mixture of colors can be determined by graphic interpolation inside the boundaries of the chart. The x and y axes of the coordinate system were determined empirically by psychological studies in color matching from three standard color samples. Figure 6-2 shows the effect of the removal of a 20A band at 5550Å. The peak of visual color response of the eye occurs at 5550Å. The removal of such a narrow band of energy produces an effective shift of less than 1 percent in apparent hue toward the purple area of the diagram (e.g., the shift of the white hue C to the hue C' in Figure 6-2). For comparison, in a typical

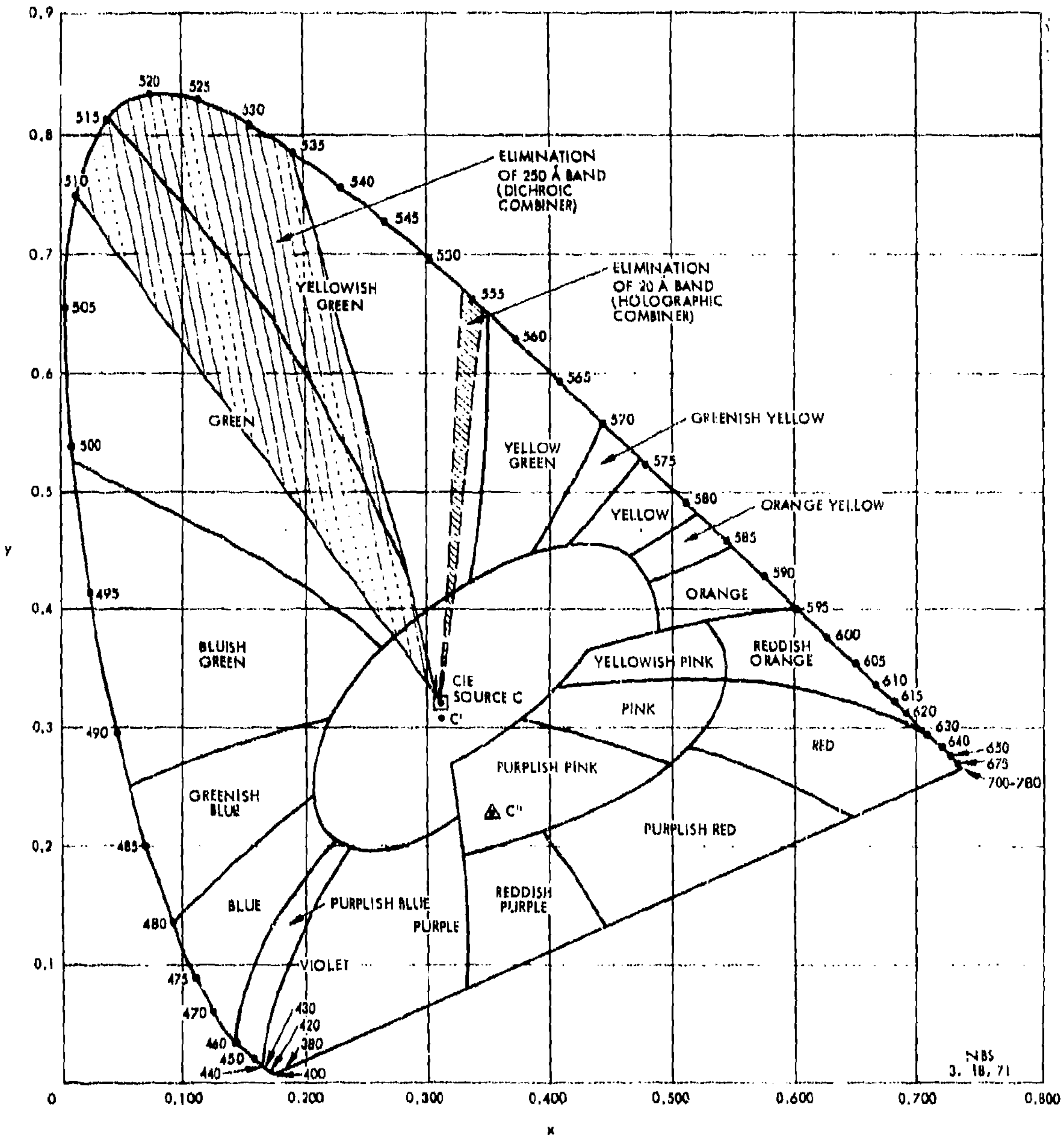


Figure 6-2. CIE chromaticity chart.

dichroic head-up display, the rejection bandwidth may be as high as 250Å, as shown in the shaded area around 5250Å in Figure 6-2. Removal of this spectral band of incoming energy will shift the centroid of the diagram to point C'', corresponding to the magenta hue of a white object viewed through a conventional HUD with a dichroic combiner. This band is shown centered around 5250A to match the more intense emission peak of the JEDEC registered P-31 phosphor. A CRT with this phosphor is typically used in present HUD systems. The P-31 phosphor is a high output, burn resistant phosphor well suited to the HUD application. Its output spectrum is so broad, however, that a wide rejection band is required in the combining glass; consequently, the hue of the transmitted image is altered appreciably. The operation of the holographic combiner therefore gives precisely the desired results from the standpoint of minimum chromatic distortion of the outside image while maintaining good reflection qualities in the spectral range containing the symbology.

A very narrow spectral source of illumination is required to match the collimating spectrum of the holographic lens/combiner. As indicated in Section 4.0, this collimating function can be obtained by either reflective or transmissive means. Ideally, the center wavelength of the spectrum of the symbology should be chosen to closely match the peak visual acuity of the average eye as shown in Figure 6-3. At this peak 5550Å point, one watt of radiant power is equivalent to 680 lumens of luminous power. A light source with very high efficiency may be found whose spectrum lies slightly off the peak of this curve. The product of that light source efficiency and its relative luminosity could be higher than the corresponding product for a source closer to the peak. If this is the case, the higher efficiency light may be more desirable.

The intensity with which the liquid crystal cell must be illuminated in order that the displayed symbols (or video) appear sufficiently bright when viewed through the optics will depend not only upon the efficiency of those optics, but also upon the cell and the manner of its coupling to the optics. The baseline configuration, shown schematically in Figure 6-4, consists of the cell (operated in the scattering mode), the holographic combiner lens,

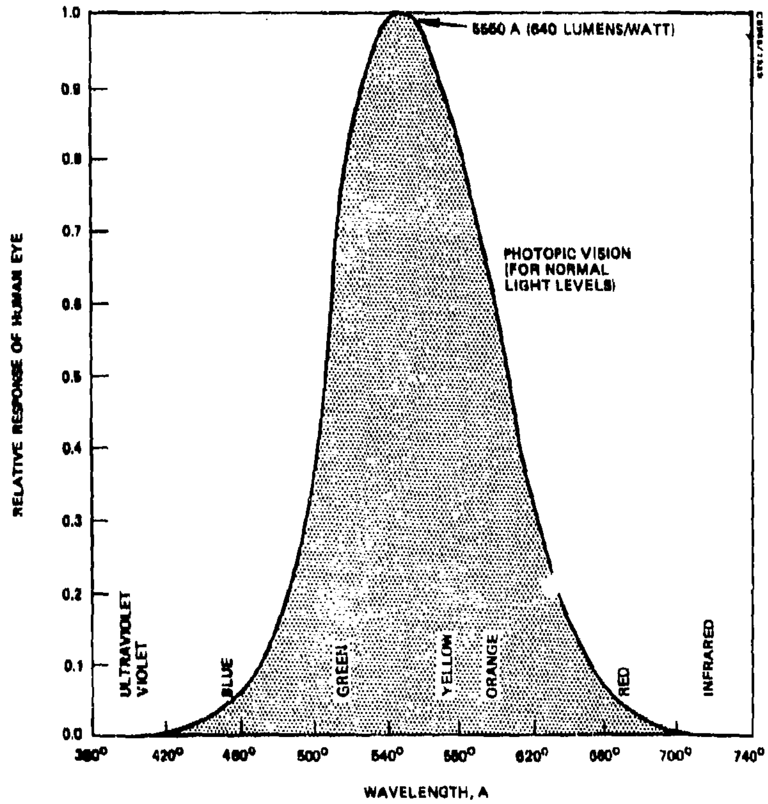


Figure 6-3. Relative response of human eye and relative luminocity.

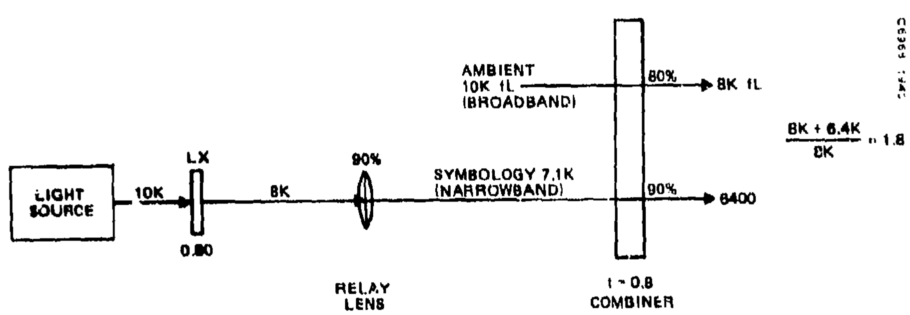


Figure 6-4. Photometric schematic of HUD optical system.

and a relay lens that forms an enlarged image of the cell in the front focal plane of the combiner. The operator thus sees an image of the cell projected to infinity against the outside scene, upon which the holographic lens has little effect. To be satisfactory, the symbols or video must appear in sufficient contrast against the outside background. As indicated in Figure 6-4 we use as a baseline assumption a sky background (cloud) luminance (brightness) of 10,000 foot-lambert, which is seen through the combiner as 8000 foot-lambert because of the 80 percent efficiency of this element to the transmission of ordinary light. The projected light forming the symbols is added to this background, so if these symbols are to show a contrast ratio of 1.8 against the background the projected symbol luminance, as seen by the operator, must be 0.8 x 8000 or 6400 foot-lamberts. Although we have here arrived at a required symbol (or video) luminance in foot-lamberts, we cannot obtain directly from this the required light flux of the symbols (or video). This could be done for a lambertian source, because the symbol luminance fills only the exit pupil of the optical system, and is zero in other directions. Thus to compute the symbol (or video) flux at the output of the optical system we would need to make use of more detail about that system. A correct answer can be computed in this way, of course, but it is much simpler and more reliable to make use of the fundamental theorem about the photometry of optical systems. This law states that except for transmission losses the luminance of an extended source as seen through any refractive-reflective system is the same as the luminance of the source as seen without the system so long as rays are not obstructed from reaching the eye. Applying this theorem we see that the scattered luminance from the liquid crystal cell must be about 8000 foot-lamberts to satisfy our baseline assumption of 90 percent transmission efficiency for the relay and combiner lenses to holographic light ($8000 = 6400/0.9 \times 0.9$). It is now a simple matter to decide the light flux required of the primary illuminator because the liquid crystal cell used in the scattering mode is approximately a lambert scatterer: Thus, if its scattering efficiency is 0.8 it must be illuminated with 10,000 lumens per square foot in order to show a luminance of 8000 foot lamberts.

An interesting observation at this point is that when it is the scattered light from the liquid crystal cell that is collected by the optical system and used to project the symbols into the operator's field of view, the primary illuminating light flux required is proportional to the area of the cell, and is independent of other details of the system. This fact favors the use of a small cell, but unfortunately most of the other optical and electrical design problems become more difficult as the cell is made smaller. On the other hand, when the transmitted or specularly reflected light is projected to form the symbols, this relationship between source flux and cell size does not hold. The difference between the diffuse and specular modes are shown in Figure 6-5. In the specular case, the primary illuminator can be a condenser system that directs all non-scattered light into the entrance pupil of the viewing optics (the aperture of the relay lens) and the required flux becomes independent of cell size, assuming a perfect condenser. If the condenser images the primary light source on the entrance pupil, the symbol luminance seen by the operator will be the surface luminance of the source diminished by the transmission loss.

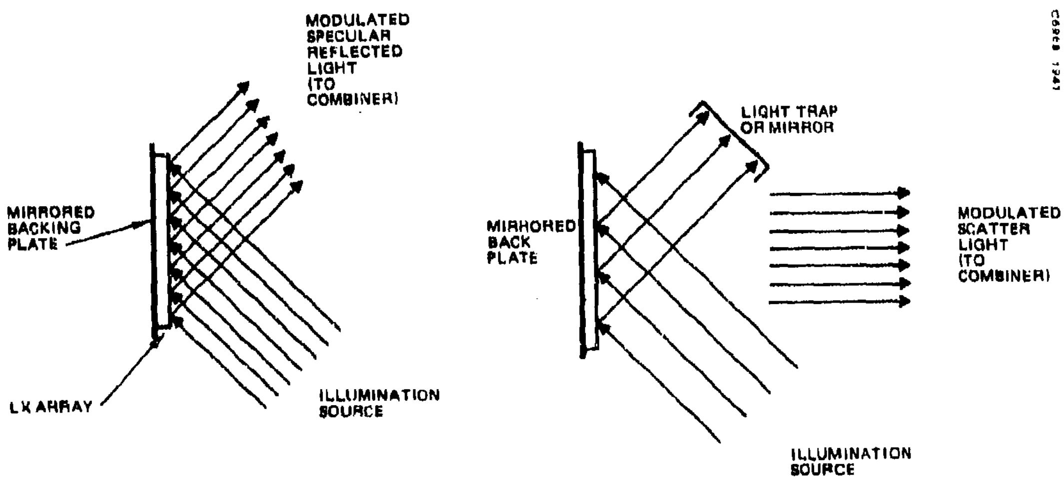


Figure 6-5. Specular versus scattering reflective LX light modulation.

In this section it has been determined that the light source must produce approximately 10,000 lumens per square foot on the face of the liquid crystal cell. A design of the optics and cell may eventually be possible with a 3 inch by 4 inch cell, but at present a cell 6 inches by 8 inches seems a more reasonable assumption (approximately 128 elements/inch). Such a cell has an area of approximately one third of a square foot and so will require a light flux of about 3300 lumens of monochromatic light at the wavelength of the holographic lens (or within a 20 Å band at this wavelength). If the system is operated at the wavelength of greatest visual efficiency (5550 Å), where the light-power conversion factor is 680 lumens per watt, this is equivalent to about 5 watts of radiant flux within the 20 Å band.

6.3 Source Tradeoff

The candidate light sources must have high efficiency in a narrow band (~20 Å) centered near the peak of visual sensitivity (~5550 Å). Broadband radiations are considered inappropriate. Two such sources, the tungsten lamp, and solar illumination are discussed. The three classes of lamps analyzed which are appropriate sources are gas discharge, solid state and excited phosphor lamps.

Figure 6-6 shows the black body radiation spectrum for a temperature of 3800°K, the maximum color temperature attainable with a tungsten filament source. If the energy within a 20Å bandwidth at 5550Å is compared with the total radiated energy between the wavelength limits plotted (zero to 50,000Å, or five microns), the spectral efficiency is 0.03 percent. This is the efficiency of a tungsten light source with a perfect optical filter of 20Å bandwidth. A practical filter would reduce this efficiency by approximately 25 percent and would consequently require a total input power of 20 kilowatts to an ordinary tungsten light source. This low efficiency is due to the requirements for narrow bandwidth and applies to any black body radiator The black body radiator is a device that emits radiation solely due to thermal agitation of the material. Its radiant emission as a function of wavelength is in accordance with Planck's equation. It is clearly inadequate for the HUD application. A source must be used which has a high conversion efficiency specifically in the narrow band of interest. As a possible compromise, the

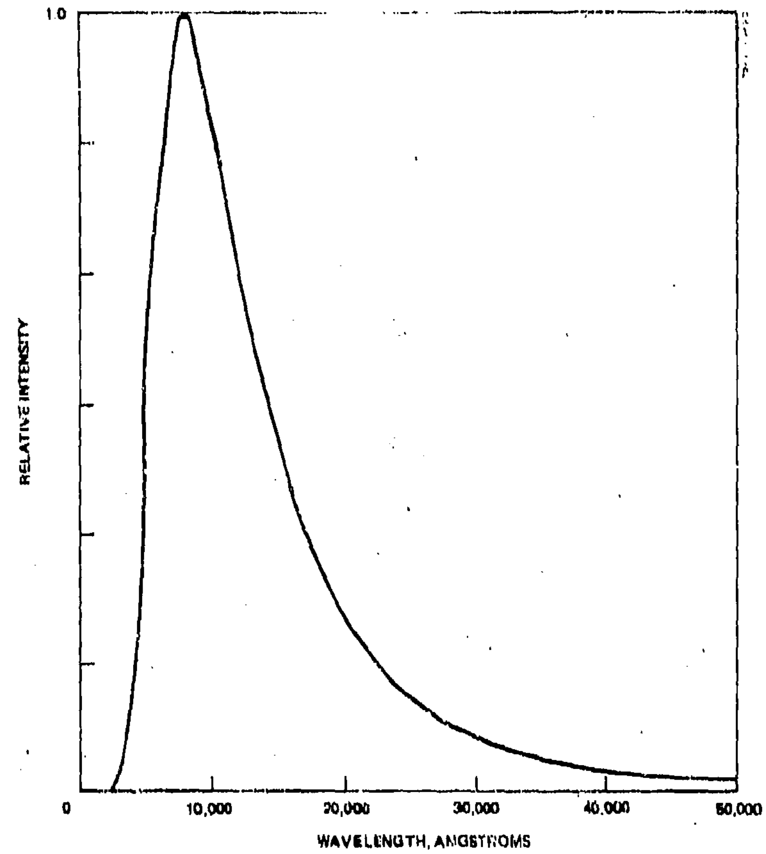


Figure 6-6. Spectral distribution of the radiation from a blackbody of unit area as given by Planck's equation at $3800^{\circ}K$.

bandwidth of the hologram may be made longer than 20Å, but the hologram becomes more complicated if the same resolution is to be maintained. In addition, the outside view becomes tinted if this bandwidth is increased. Additional effort is required to determine the optimum bandwidth.

As a possible alternative solution to the internal generation of this radiant power, utilization of solar energy has been considered. The first arguments against using sunlight is the lack of control over intermediate cloud cover and relative position of the sun with respect to the aircraft. A collection lens and filter would have to be installed in the cockpit and servoed to the sun during aircraft maneuvers. An internal light source would be required when an unobstructed view of the sun cannot be attained. The intensity of the sun would provide an order of magnitude more light than required when using a lens aperture of 6 square inches. A diverging lens could be used, and a pointing accuracy of 10 minutes of arc (three times the

angular subtense of the sun as observed from the earth) would be required of the servo system. At this time, the arguments against this system seem to outweigh the benefits of the power savings, and the following discussion will develop the concepts of two moderately low power light sources.

The first class of lamps considered produce a narrow spectral emission band by gas discharge. A variety of lamps are manufactured to generate narrow spectral bandwidths at various wavelengths. These glow discharge lamps, called Osram Lamps, emit a characteristic glow corresponding to the arc discharge characteristics of the element in the cathode. One such lamp with a thallium cathode emits a strong line at 5350Å, a wavelength suitable for this application. The 5350Å line is at about 90 percent of visual response as seen in Figure 6-3. Therefore, 6 watts of radiant energy should be provided. Osram lamps require low radiated power from the plasma glow, because the lamp must operate at very low cathode currents with a high field at the cathode. As a result, the cathode remains cool, and the primary radiation is at those wavelengths corresponding to the energy bands of the element with the highest transition probabilities. If the cathode current density is increased, secondary effects broaden the emission bandwidth. In general, these effects are collisions, self-absorption, re-emission, and other heating effects. As the elements are heated, black body radiation effects lower the efficiency and increase the power output to a level usable for this application. At this high level, the gas does not operate in a glow discharge mode with the emission characteristics and cathode field as described above. Instead, it operates in an arc discharge mode.

An abrupt change in line broadening and a rise in the background white light (continuum) takes place in the emission of an arc lamp. Thallium iodide arc lamps have been built recently for narrow band illumination in oceanographic research. Currently manufactured arc lamps are approximately 5 percent efficient in the required 20Å bandwidth at 5350Å. Figure 6-7 shows a commercially manufactured arc lamp. Assuming a 5 percent efficiency, a 120 watt lamp is required to provide the 6 watts of radiant power. A current limiting power supply is necessary, since the lamp is a negative resistance. Assuming an 75 percent power supply efficiency, 160 watts of input electrical power are required to provide the required illumination.

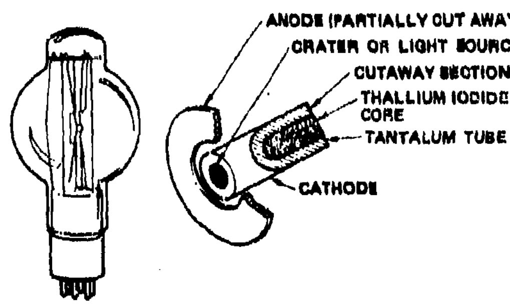


Figure 6-7. Concentrated-arc lamp.

The second class of lamps to be discussed is solid state devices. This includes light emitting diodes, electroluminescent panels, and solid state lasers.

Solid state light emitting diodes (LED) have been manufactured for some time, but no efficient materials have been found for room temperature operation in the 5550Å portion of the spectrum. There is a strong drive throughout industry to produce an efficient solid state green lamp, but it has met with little success. The best green LED is made from gallium phosphide and has been reported to produce efficiencies of approximately 0.1 to 0.6 percent in a 250Å bandwidth. The devices are very low power, the nominal power dissipation being less than 0.5 watt. If the entire panel were illuminated with LED power, a large number of devices would be required in an array. With a possible efficiency of 0.5 percent, an input power of 12 kilowatt would be required and 10,000 devices would have to be assembled (and cooled to nominal ambient temperature) to produce this power. Illumination of a portion of the display area at any particular time (depending on the symbology being presented at that time) adds complexity to the system and still would not provide a solution for the illumination of the entire panel.

Electroluminescent panels are radiating devices that are fabricated as a sandwich structure with a phosphorescent material between two electrodes. Radiation takes place as a result of direct electron recombinations in the phosphorescent layer. The process is very inefficient due to the high fields required for ionization. Electroluminescent panels have been manufactured

for several years, with a lack of success in developing a very bright device. An example of a state-of-the art device would be an electroluminescent panel consisting of a ZnS: Mn, Cu phosphor panel, operating at 100 Vdc and 2.5 ma/ cm^2 power input with a 100 foot-lambert output. The conversion efficiency is 0.1 percent, but the radiated output is in a 500Å bandwidth (at a peak wavelength of 5800Å). The brightness and efficiency is far below that required for this application and, since this disclosure represents roughly the state-of-the-art in electroluminescent panels, they should not to be considered for the advanced HUD design.

The light source must provide a conversion efficiency significantly higher than 1 percent, preferably higher than 10 percent, to be useful in the HUD system. Solid state lasers can be considered for this application, since they are more efficient than light emitting diodes or electroluminescent panels. Their operating conditions, however, are not favorable for a practical airborne display. The materials require cooling to cryogenic temperatures to emit the characteristic high energy, narrow band radiation. A report has been published on the laser activity of $CdS_{(x)}CdSe_{(1-x)}$ under electron beam excitation at cryogenic temperatures. The electron beam was accelerated to 50 KV, and operation was monitored at liquid nitrogen temperature ($77^{o}K$) and at liquid helium temperature ($4^{o}K$). The material exhibited a broad band fluorescence at low current densities, and at a critical current density, the bandwidth narrowed and laser action occurred. The emission wavelength is tunable over a broad range by varying the relative concentration of sulphur and selenium in the crystal. At x = 20 percent in the above formulation, i.e., with 20 percent cadmium sulfide and 80 percent cadmium selenide, the emission wavelength is approximately 5400Å in a very spectral band. The efficiency is approximately 10 percent when operated at the liquid nitrogen temperature, and it increases to approximately 14 percent if the temperature is lowered to that of liquid helium. Although this emission wavelength and efficiency appear very attractive, the disadvantage of the cryogenic cooling and the electron beam bombardment requirements do not appear practical. A solid state laser may be developed in the future with direct transitions of low energy electrons in a tunneling mode, but it is almost

certain to require cryogenic cooling for operation. For this reason, the solid state laser devices using direct electrical transitions are not considered practical for the HUD development. More conventional laser systems, both gas and crystal, either operate at low efficiencies or at a poor wavelength for the HUD application even though cryogenic cooling is frequently not necessary for their operation. For example, the helium-neon laser operates at room temperature and is a common tool in technology today, but the radiation efficiency is lower than 1 percent, and the radiation wavelength is at 6328Å. Operation at this wavelength is unfavorable because the reduced visual sensitivity in the red spectral region. One potential type of laser that may be of interest is the liquid dye laser currently under investigation. Materials in this category are still too new to evaluate from an efficiency standpoint, but a breakthrough in this area may yield a usable laser source.

Conventional phosphors excited by a high energy electron beam or by an ultraviolet photon beam are a third class of light sources. Cathodoluminescence can be generated by a flood of high energy electrons striking a phosphor surface in a vacuum tube (cathode ray tube). The output energy is diffused over a large area and cannot be well collimated. A typical narrow band phosphor suitable for this application is P44, which is a narrow band phosphor emitting in a narrow band between 5400 to 5450Å. This phosphor is specified as emitting 200 foot-lamberts at 20 KV with 0.5 microamps per square centimeter excitation. The efficiency is 3.3 percent for the 50Å bandwidth. Extrapolating linearly (although the phosphor efficiency actually decreases with increased current loading) to obtain the required 6-watts (since it is not at 5550 Å) output in a 20Å-bandwidth; the beam power must be 600 watts. This is clearly unreasonable for a CRT faceplate power loading specification and would require an extremely high emission cathode to generate the beam current of 30 milliamps. Phosphors can also emit radiation under ultraviolet photon excitation. Photoluminescence is the process of converting photon radiation of one wavelength to photon radiation at another wavelength. The conversion of interest is from the ultraviolet radiation of the mercury arc at 2537Å to the photoemission at 5440Å. The efficiency of the 2537Å source and the conversion efficiency of the phosphor are both very high, but as in any phosphor

surface, the disadvantage remains that the radiation is diffused over a large area and cannot be well collimated. A large flat panel of this type with a mercury arc source irradiating a phosphor panel has not yet been fabricated, and an optimum design is yet to be determined. A possible configuration is shown in Figure 6-8. The mercury line power generation and the conversion efficiency are both simple to evaluate with straightforward laboratory experiments. A production device should be relatively inexpensive to fabricate. Mercury arc lamps have been in production for quite some time, and the reported conversion efficiencies (at 2537Å) are approximately 90 percent. The phosphor of interest is an unregistered phosphor manufactured by General Electric Chemical Products Section which carries their catalog number 118-2-34. The chemical compound is $Gd_2O_2S:Tb$. It is specified to have a very intense, high purity peak at 5440Å and a close secondary peak at 5485Å. Both of these peaks are approximately 20Å wide, but the 5440Å peak is more intense as seen in Figure 6-9. The combination of the mercury arc and the phosphor utilizing only the 5440Å peak is expected to yield a power conversion of approximately 25 percent. This is significantly higher than the other sources studied. If it is determined in future studies that the spectral bandwidth can be increased to 100Å, the efficiency will be increased to approximately 40 percent. Since the phosphor surface emits diffused light, the projection system must collect this to project to the holographic lens. Assuming a collection efficiency of 50 percent, which should be attainable with a lens design around F:1, the power requirement is approximately 50 watts for a 20Å band. Increasing the bandwidth to 100Å results in a further lowering of required power to 35 watts.

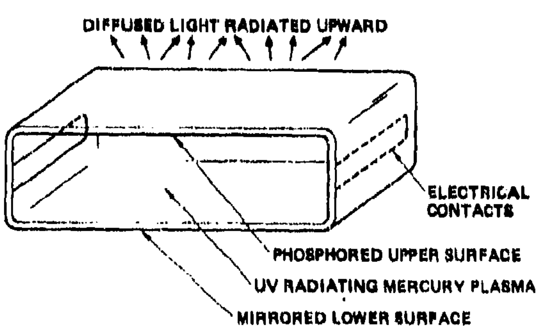


Figure 6-8. Possible configuration of mercury arc lamp with phosphor conversion to 5440 angstrom radiation.

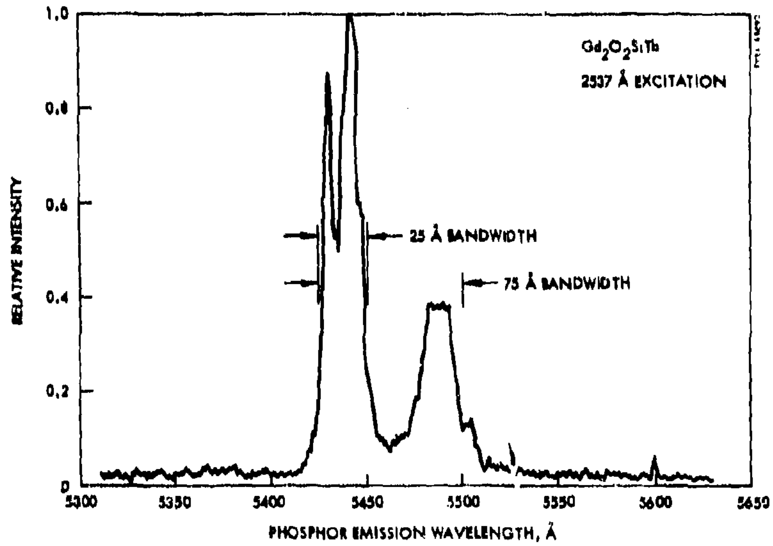


Figure 6-9. Phosphor emission wavelength.

6.4 Conclusion

In summary, the two practical lamps for the advanced HUD appear to be the thallium arc lamp for a point source collimated light and the mercury arc activated $Gd_2O_2S{:}Tb$ phosphor panel lamp for a diffused source. Due to the operation of the liquid crystal cell, the collimated arc source is recommended for use with the reflective liquid crystal cell in a scattering mode. The diffused panel source appears to be applicable to the transmissive liquid crystal cell designs. Table VI-1 presents a summary of the lamp types studied with operating conditions and relative ratings as to their utility in an advanced HUD. A Thallium lamp of the required intensity is within the state of the art and is the recommended source for the baseline design.

TABLE VI-1. CANDIDATE LIGHT SOURCE TECHNOLOGIES

Lamp Type	Efficiency		State of Development	Power Required		Relative Cost	Wavelength	Notes
	20Å Band	100Å Band		20Å	100Å			
Solar System							Broad	Complex servo system required for tracking/ Nighttime illum required.
Tungsten Lamp	0.03%	0.15%		40KW	8KW	Low	Broad	Inefficient Not Applicable
Laser $CdS_{(x)}CdSe_{(1-x)}$	~12%	~12%	Research	80W		High	Any Available	50KV electron excitation/Undesirable cryogenic cooling
Electro-Luminescent	0.006%	0.03%	Research	Astronomical			5800Å	Inefficient/ Not Applicable
Thallium Arc Lamp	~5%	>15%	Within State of Art	120W	40W	Low	5350Å	Point source (scattering reflective LX) Power supply required. Collimator required.
Mercury Arc and Phosphor	25%	40%	Laboratory	50W	35W	Low	5440Å	Diffused source (transparent LX) Power supply req'd.
Electron Beam Activated Phosphor	1.6%	3.3%	Laboratory	1200W	600W	Med.	5440Å	20KV electron excit. (Power assumes 50% CRT gun efficiency)
Light Emitting Diode	0.15%	0.5%	Production	12KW	2.5KW	High	Several Alt (one at 5500Å)	Good for discrete point illumination

7.0 BASELINE SYSTEM DESIGN

7.1 Introduction

The requirement for a wide angle high brightness HUD with a design goal of a 60 degrees azimuth and 45 degrees elevation field of view has been established. Current operational HUD technology, using the classical optics approach with a projection lens and a partially reflecting combining glass, have been limited to a field of view of less than 20 degrees. The primary reason for this limitation is the large lens that is required to provide a large field of view and a reasonable exit pupil with a cockpit viewing distance of 26 inches. A lens and combiner glass larger than 1-foot in diameter would be required to provide the 30-degree field of view with no allowance for lateral motion or exit pupil at the edge of the field. A nominal allowance of 3 inches causes the size of the lens to approach a 20-inch diameter. An increase in the field of view to 60 degrees would force the lens diameter to increase to approximately 3 feet. This would clearly be too large, complex, and expensive to consider for tactical fighter aircraft.

An advanced approach to wide angle HUD has resulted in the application of holographic optics to provide the functions of both the conventional combining glass and the projection lens. Eliminating the large projection lens is a major improvement, and the formation of a uniform holographic lens may be easier than manufacturing a high quality, uniform curved dichroic interference filter. The operation of the holographic lens is not critically dependent on film thickness as is the dichroic interference filter. The effect of a change in the holographic lens film thickness is a change in the reflection efficiency, as opposed to a change in focal length or reflection wavelength. Consequently, the production application of the dichromatic

gelatin (or alternate) coating on the curved combiner surface should be much simpler than the multiple layer deposition required of the dichroic mirror. Subsequent laser exposure and processing are far from routine procedure at this time, but the technology is still new and many production techniques will be developed.

The second parameter discussed in the design goals for the advanced HUD is the brightness required. One of the fundamental requirements of any HUD is that it not distort the view of the outside world. This distortion includes geometric distortion, undue attenuation, and tinting of the view. Many current HUD systems utilize a broadband reflector to achieve a "neutral density" reduction in the outside world view. The symbology is then partially reflected (broadband by approximately the same fraction as that of the outside illumination) and combined with the outside illumination. The disadvantage of this approach lies in the attenuation of the outside view and the inefficient utilization of the symbology luminant power. In an attempt to reduce the attenuation of the outside view and increase the efficiency of the HUD symbology luminance, some HUD combiner surfaces are made with dichroic or trichroic reflectors. (The primary difference between the dichroic and trichroic combiners is the number of coatings in the layered reflective surface, which controls the bandwidth, maximum transmission, cutoff slope, and sideband rejection.) The problem with the narrow band reflector involves the tradeoff between efficiency and tinting of the outside world. The narrower the filter bandwidth, the lower the efficiency. Conversely the wider the filter bandwidth, the greater is the tinting effect of the outside scene. This tradeoff becomes heavily weighted towards the narrow filter if a highly efficient narrow band source of projected symbology is used.

The luminance design goal of the advanced HUD is to provide a maximum display brightness of one shade of gray above the brightest outside image. For design goal purposes, a 10K fL ambient was selected. This is equivalent to solar reflection from a white cloud. The CRT is not capable of providing the brightness required to see sensor video against such a background. This is true because the gray shade rendition necessary for sensor video requires very high contrast levels.

The advanced approach to providing high intensity symbology is to utilize a liquid crystal light modulator and an efficient narrow spectrum light source. The light source can be made efficient, requiring lower power than required by a CRT. The additional power required by the liquid crystal display electronics is very low, providing an integrated display that is low power, narrow bandwidth, and high reliability. The holographic lens system and the liquid crystal technologies offer significant improvement in the operational capabilities for an advanced HUD. Combinations of these technologies with existing classical optics designs and with CRT projection systems or alternate light modulator designs will result in potential improvements over current systems, but will not satisfy the desired design goals of a wide angle, high brightness HUD.

7.2 Cockpit Installation Configurations

In the initial phase of the program, major consideration was given to providing a baseline HUD design suitable for installation in a current configuration aircraft. The A-7 was selected as the aircraft, because its primary mission, A-G weapon delivery, corresponds to the primary mission for which the advanced HUD is being considered. However, after the requirements analysis established the required large field of view, a study of the A-7 indicated that installation of a wide angle HUD is not practical. The vertical and horizontal field of view design goal is not realizable in the A-7 because of obscuration by the A-7 airframe structure. Accordingly, the A-7 cockpit and canopy structure was utilized as a departure point. The advanced HUD baseline design is therefore based on an aircraft, such as the A10, that has much better forward visibility than the A-7. It should be stressed, however, that the technologies and concepts presented in this study could be applied to the A-7 to provide a significantly improved head-up display (both in field of view and brightness). It should be noted that a completely unobscured field of view is not necessary to realize certain advantages of a larger field of view HUD. The symbology on the HUD can be presented over the obscured area, and the tracking reticle will indicate target position even when the target is visually obscured by the structure.

It was beyond the scope of this program to develop a detailed optical design and aircraft physical installation. A simplified design was developed to illustrate the concepts involved. All of the installation sketches illustrated herein are based on a cockpit configuration similar to the A-10. The A-10 cockpit field of view closely matches the advanced HUD capabilities. The wide field of view allows greater utilization of off-axis homing missiles to improve the overall system effectiveness by providing strike capability in situations previously not within an attack envelope. It will be observed that the sketches of the advanced HUD have direct (as opposed to folded) optical paths. In any of these systems an additional optical element (mirror) can be introduced to fold the optical path and thus increase the total optical axis length to ease the requirements on some of the lens design parameters. In addition, the lens and the liquid crystal module may be tilted with respect to the optical axis to reduce the field angle requirements and to increase the light gathering capability.

Figure 7-1 shows a canopy sketch of the pilot's field of view through the advanced HUD in the azimuth and elevation profiles. The display could be shifted downward (either fixed or selectable) to provide coverage below the direct nose view if a transmission holographic lens is made large enough along the vertical dimension.

7.2.1 Alternate System Configurations

Figure 7-2 shows the recommended baseline system design, which utilizes a flat transmission holographic lens array and a reflective liquid crystal display. These components were chosen because they represent the most developed form of holographic optic and liquid crystal technology. The baseline HUD utilizes a short thallium arc lamp and a collimating lens for the illumination system. The light is focused to a spot in the area of the perimeter of the relay lens (after specular reflection from the liquid crystal), where it is restricted from transmission to the holographic lens

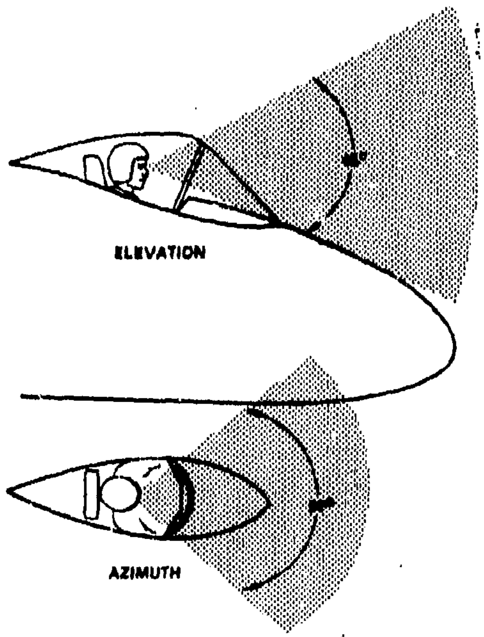


Figure 7-1. HUD field of view.

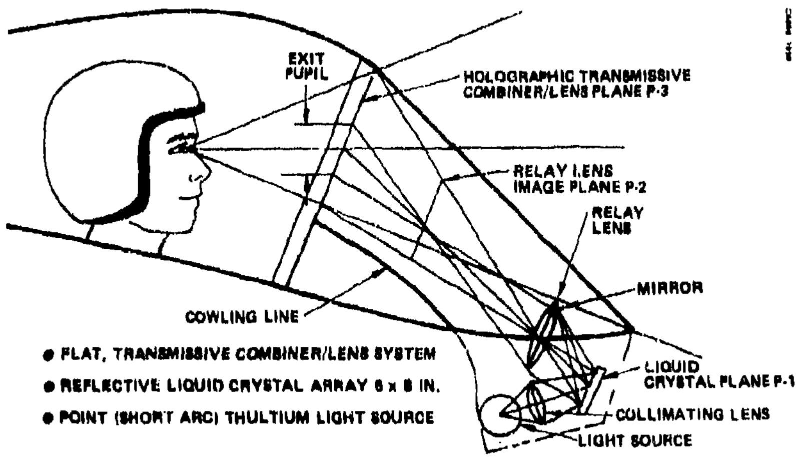


Figure 7-2. HUD baseline system design.

by a small masked area. The diffused reflection from the liquid crystal fills the relay lens, which focuses this diffuse reflected object plane P-1 to the magnified image plane P-2. Rays from this image plane intersect the holographic lens plane P-3 within the exit pupil area where they are collimated for viewing. The cockpit volume and panel space using this design are small. The efficiency of this is highly dependent on the collection efficiency of the collimating and relay lenses. In addition, if the display consists of symbology, most of the light is specularly reflected and lost. The lenses will be large aperture elements, and the liquid crystal material can be specially formulated to control the scattering angle to improve the collection efficiency. In addition, a small mirror can be placed at the mask position at the focal point of the specularly reflected rays, and this point becomes a second source of illumination. The efficiency can be significantly improved in this manner. The primary areas requiring attention when considering an actual design for use in an aircraft are: 1) increasing the length of the optical axis in order to increase the focal lengths of the lenses, and 2) decreasing the off axis angle between the line of sight and the projection optical axis to reduce the holographic lens aberrations. A modification to the relay optics in the baseline system design allows the use of the specular reflected light instead of the diffused reflective light for the imagery. In this design, the specular reflected light is focused to a small aperture where the image is collimated and magnified before going to the relay lens.

Figure 7-3 shows an alternate to the baseline advanced HUD design. The relay lens and projection path are identical to the baseline system; the difference between the two designs being in the liquid crystal and light source. In this system, the liquid crystal transmits diffused light from a phosphorescent source to form the image; consequently, the mask used in the baseline system is not necessary here. The same optical considerations apply to this system as applied in the baseline system. The display module circuitry must be made transparent in order to project through it. Silicon on sapphire circuitry should be satisfactory for this application. It must be stressed that the liquid crystal configuration and the lamp design have not

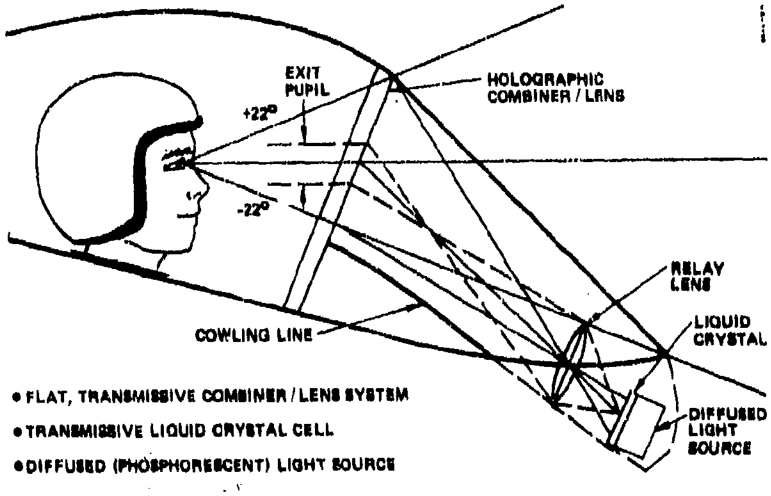


Figure 7-3. HUD alternate No. 1 system design.

been proven. The reason the design has been proposed is the higher efficiency of the diffused light source (25 percent) as opposed to the arc light source (~5 percent). The diffused source and the reflective liquid crystal module cannot be combined in one design, because the diffused source cannot be collimated as required in the reflective cell optics design.

A second alternate design is shown in Figure 7-4. This concept uses a holographic lens design incorporated into the contour of the canopy.

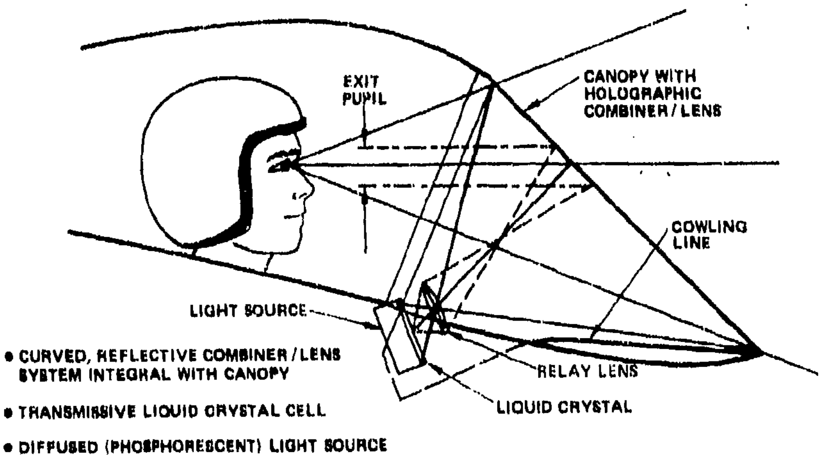


Figure 7-4. HUD alternate No. 2 system design.

The structure and substrate shown for the flat holographic lens in Figures 7-2 and 7-3 are not required with this design. The design is shown with a transmissive liquid crystal cell; however, the optics could be folded to incorporate the reflective cell. This design is more advanced than the flat substrate holographic lens array designs, because of the wide field of view of the relay lens. The problems anticipated in coating the curved canopy with holographic film emulsion, and uniformly exposing and developing the film over such a large area have yet to be solved.

7.3 Expected Performance and Physical Parameters

The major factors which determine the performance of a head-up display are field of view, brightness, and imaging accuracy. The parameters for the advanced HUD are summarized in Table VII-1. The imaging accuracy of a 45 x 60 degree field of view HUD employing a flat transmissive or reflective holographic lens array were presented in Section 4.5 of this report. Curves defining the collimation errors, distortion, and binocular disparity were presented. These errors, in the range of 1 degree, are significantly worse than the design goal; however, it is anticipated that better design techniques and compensation schemes will reduce imaging errors. Errors of a conventional head-up display with a 45 x 60 degree field of view would be significantly worse.

The liquid crystal matrix display array illuminated by the thallium arc lamp, described in Section 6.0 of this report, will result in fully legible symbology in a background ambient of 10K fL. The ability to provide gray shades and color is discussed later in this section.

In order to provide the desired 1-mrad resolution, a matrix array of 1024 x 768 elements is recommended for this application. The baseline utilizes a 6- x 8-inch array with 128 elements per inch. As the state of the art advances, the array size can be reduced.

The source of video for the liquid crystal array must be generated in a television format. Electro-optical sensor video is normally provided in such a format. Symbol generation in a television format is easily achieved.

TABLE VII-1. ADVANCED HEAD UP DISPLAY SPECIFICATION

Field of View	60 degrees horizontal by 45 degrees vertical
Brightness	Provides 1.8 contrast ratio with 10KFtL background (8KFtL)
Transmission	90 percent (no tinting of outside scene)
Color	Narrow band centered at approximately 5350Å
Accuracy	<25 mrad over entire FOV (to improve with better design techniques)
Resolution	Total 768 x 1024 elements (approximately 1 mrad)
Size	Combiner 21 x 28 inch outside dimensions (1/4-inch thick) Projection source estimate 15 x 8 x 10 inches
Weight (total)	25 pounds
Power	200w
MTBF	2000 hours (Recommend lamp replacement at 1000 hours)
Functional Capabilities	Daytime Sensor Display Gray Shade Rendition Growth Potential to Provide Color TV Compatible Display Format

Input video in a television format is required, because it is the easiest means of addressing the liquid crystal matrix display. Random access addressing to provide stroke written symbology would require an excessive number of input-output lines in the array.

The estimated physical parameters of the baseline configuration advanced HUD shown in Figure 7-2 are also presented in Table VII-1. The size dimensions are largely determined by the combiner and the projection source. In the baseline configuration, the combiner is a flat transmissive hologram array supported across the canopy structure. The projection source includes the thallium arc light source, power supply, light collimator, liquid crystal array, and associated electronics. It does not include the symbol generator. The alternate configuration employing the diffuse flat light source would be smaller.

Total weight is based on a 1/4" plexiglass combiner with an aluminum frame and the projection source with a high efficiency power supply. The total power of less than 200 watts consists of 120 watts for the thallium lamp to provide the required illumination and 20 watts for the liquid crystal electronics. Assuming the efficiency of the arc power supply is 75 percent, approximately 60 watts are lost in the power supply. Estimated MTBF of 2000 hours is based on an estimate of the reliability of the complex LSI liquid crystal drive circuits and the arc source power supply. If a diffuse light source is used, a higher reliability can be expected.

7.3.1 Gray Shade and Color Rendition

Depending on the aircraft mission and sensors on-board, it may be desirable to project pictorial sensor video on the head-up display. This is particularly true when sensors are available which provide visibility in limited visibility condition (overcast, rain, nighttime). Candidate sensors are LLTV and FLIR which require a display format (azimuth versus elevation) compatible with direct viewing through the windscreen. The superposition of sensor video on the outside world enhances visibility while allowing head-up operation of the aircraft is attractive. Display of sensor video on the HUD places two constraints on the HUD design. The first is

compatibility with the input format of the video. The second constraint is the display must be capable of providing reasonable gray shade renditions.

The video format from most FLIR and LLTV sensors is a TV raster type format made up of adjacent successive raster lines refreshed at a field rate of 60 Hz to eliminate flicker. The number of raster lines is a function of the resolution of the sensor system.

Liquid crystal cells have been observed with a contrast ratio of approximately 2500:1 with an applied voltage swing of 40 volts. This contrast ratio is dependent on viewing angle. The maximum contrast ratio is observed at an angle of 90 degrees to the surface (directly on axis in a transmissive system). Such a contrast ratio would provide over 20 $\sqrt{2}$ shades of gray.

The achievable gray shade capability of the HUD system is not limited by the liquid crystal. Since contrast ratio is the key parameter in determination of shades of gray, the limiting factor is brightness of the video as compared to the background. As a design goal, it was stated that symbols should be legible with full resolution (1 mrad) with a 10K fL ambient. It was also determined that a contrast ratio of 1.8 is required to meet this design goal. The system was designed accordingly. Given the 10K fL ambient, 1.8 contrast ratio design point, a curve can be derived to show the gray shade rendition capability of this display with lower background ambients. This is shown in Figure 7-5 for full and degraded resolution capability.

Accordingly, under worst case ambient background conditions, such as when flying toward direct solar reflections from large clouds (10KfL) the advanced HUD, provides easily viewable symbology. The same high resolution HUD would provide five shades of gray against a nominal daylight background of 1000 fL. With 3-mrad resolution, seven to eight shades of gray would be provided.

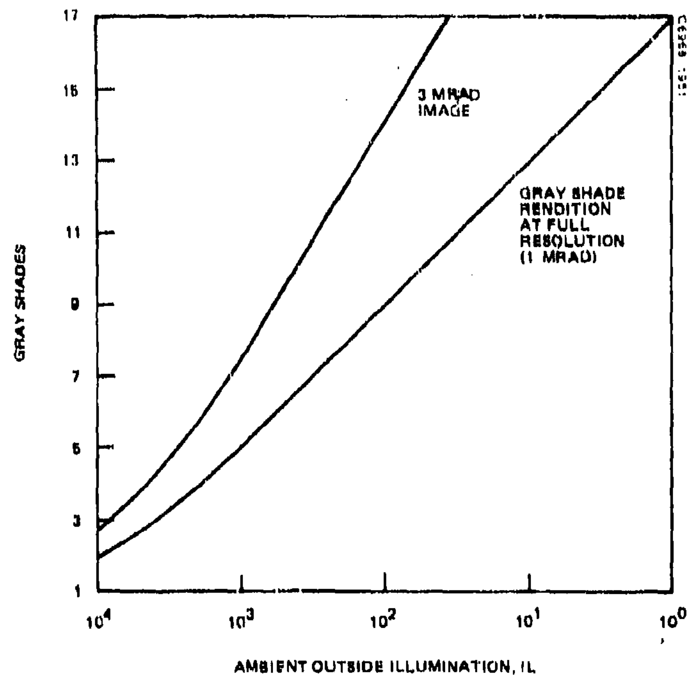


Figure 7-5. Gray shade rendition of advanced head-up display.

A design goal for the advanced HUD is the capability of providing color. This is desirable because of the additional information transfer capability possible by using color coding to reduce symbology clutter. The state-of-the-art in liquid crystal and holographic optics technologies is too premature to specify design details for a multi-color HUD. However, color display capability has been considered. For the liquid crystal, the mixing of dyes in the material or the use of multiple arrays with filters could be utilized. The concept of a sequential color television system could also be applied. In this case, three successive frames are presented on the same display each one filtered by one of the primary colors to create a full-color display. One drawback of the sequential color approach is the high speed at which the frames must be presented to avoid flicker. The normal 60 field per second flicker-free television format must be presented at 180 fields/second.

The other major consideration for a multi-color HUD is the spectral dependence of the holographic optics. At the present time, work is being done in the development of multi-layer holograms. Conceivably, each layer would be made sensitive to a different portion of the visible spectrum. When aligned, the resultant display would exhibit full color capability.

8.0 FUTURE DEVELOPMENT

The two technologies, described in this report, which the advanced HUD are dependent upon, are at an early stage of development. Based on the results of this study, these technologies can be combined to provide a head-up display with significant performance improvements over HUDs incorporating today's conventional techniques. However, advancements in the field of both liquid crystal and holographic technology must be made before such a system can be developed. In this section, the specific areas where these technologies must be advanced and a development schedule are described.

8.1 Liquid Crystal Technology Advancements

The two basic types of liquid crystal material described and recommended for possible use in the head-up display are the nematic dynamic scattering and the nematic field effect cells. The Nematic dynamic cells are the most mature technology at this time. Alphanumeric read-out and key boards are being manufactured utilizing this material. As such, it is the type of liquid crystal material most suitable for near term use in an advanced head-up display. The major development problems involving this type of material are temperature sensitivity and the dependence of contrast on the angle of viewing. The temperature dependence exhibits itself as a variation in the conductivity and viscosity of the material with temperature. This problem is expected to be resolved within the next two years by commercial and military research.

The second problem area is that of the angular dependence when viewing the liquid crystal matrix. The contrast and brightness are dependent on viewing angle. This problem is being seriously attacked by potential users interested in the direct display application. However for the head-up display due to the optical processing of the image this is not as critical a problem since the array is not viewed directly.

The nematic field effect liquid crystal material is at a much less advanced state of development. However, the advantages it affords in simplification of the optical system makes it a major candidate. This advantage stems from the light modulation by means of polarization rather than diffusion. This allows the use of a more efficient illuminating source and removes the requirement for a highly collimated source of light since the liquid crystal achieves the collimation. A disadvantage of this material is its switching characteristics which make gray shade rendition more difficult. Ideally, this property could be improved by modifying the material. It should be mentioned, however, that advancements in the gray shade capability of this material are unlikely without research. This is because most of the work on numeric displays is not concerned with gray shade rendition, and TV type flat panel display research is mainly directed at the nematic scattering material.

8.1.1 Related Technology Advancements

Two other major areas of technology which must be considered for the development of the liquid crystal matrix display are the illumination source and the LSI technology necessary to provide the drive circuitry and addressing of the liquid crystal matrix. Two potentially attractive sources of illumination were described in this report. The thallium arc source is suitable when using a reflective nematic scattering liquid crystal matrix. The mercury arc and spectral phosphor is suitable for use with the transparent field effect nematic liquid crystal matrix. Neither of these sources have been built in a configuration suitable for the HUD. However, similar sources have been built, and it is considered a minimum risk development.

The LSI Matrix which provides the addressing and drive circuitry function for the matrix is being developed in MOS technology to provide a TV compatible display using nematic scattering reflective liquid crystal material. A low resolution demonstration display of this type is being developed by Hughes Aircraft Company under contract with the Air Force Avionics Laboratory. Hence, the reflective display is much closer to development than the transmissive liquid crystal display. One problem of a large LSI array is the manufacturing yield which can be expected. With the many elements necessary to obtain a high density matrix array, it is likely that cell failures will exist. This yield is improved in present LSI circuits by such techniques as pad relocation and discretionary wiring. These techniques involve the replacement of a bad cell by wiring over to an extra cell of the same type located elsewhere on the LSI chip. This is not possible with the HUD application because of the display format. That is, the relative orientation of the cells spatially must not be changed. However, it is anticipated that as production techniques become more established, the production yield of complex arrays will improve. Figure 8-1 illustrates the expected improvement in the yield of the LSI manufacturing.

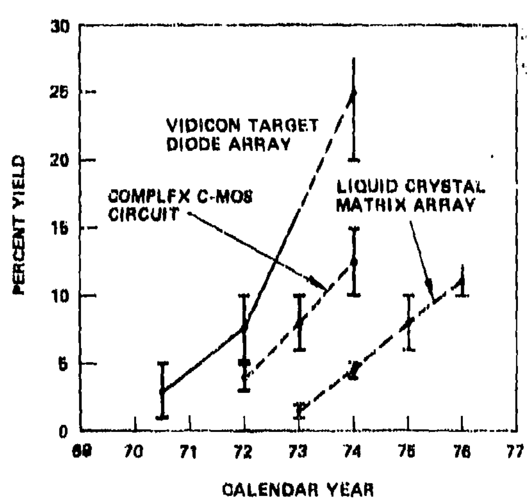


Figure 8-1. Wafer yield prediction.

In order to develop a transparent Liquid crystal display which allows the use of field effect material and a more efficient, simpler light source and optics, the drive electronic LSI chip must be transparent. The silicon on sapphire integrated circuit technology provides this capability. The sapphire has the advantage of providing better circuit isolation than silicon and hence results in higher operating speeds. It also is nearly clear in the visible spectrum. This is the ideal LSI circuitry for the transparent liquid crystal application. The most complex silicon on sapphire LSI circuitry developed to data is a 5, 000 bit read only memory. Although the type of circuitry necessary has not been developed, it is not considered a high risk development.

8.2 Holographic Optics Technology Advancements

Technology areas where better understanding of the application of hologram arrays to HUD systems is required are discussed below. These areas are the logical next step in development of this application.

8.2.1 Parametric Design Studies

Extensive computer ray tracing is required to evaluate a single system design. A program is needed to provide performance data for a range of values of ϕ, d, f and FOV. This would provide the design tools necessary to make system tradeoffs and aid in defining the optimum system geometry to minimize sources of inaccuracies.

8.2.2 Curved Substrates Analysis

The use of curved substrates can potentially improve system performance in the areas of local distortion, binocular disparity, and pupil errors. Design techniques must be developed that will allow testing and optimization of curved substrate designs. Source surface curvature is included in these techniques, which can simplify the relay optics design and improve system performance. These techniques would be applied to HUD system design, and the predicted performance of optimized systems would be obtained.

8.2.3 Dispersion Compensation

A primary tradeoff in present holographic HUD system designs is image resolution versus image brightness (source power) requirements. This tradeoff arises from the chromatic dispersion of the asymmetrical hologram optical elements. Compensation for this dispersion is possible but is a difficult design task, since it requires another (smaller) hologram array in the optical system. The elements of both arrays must be optimized to allow a wavelength spread in the source while maintaining projected image quality without tinting the outside scene. A more reasonable source spectral bandwidth is 100 Å. The objective would be to achieve 1-mrad resolution with this bandwidth, while maintaining image quality.

At the present time, Hughes is in the process of developing a small multi-element holographic array on a plastic spherical substrate. The application is to provide a visor helmet-mounted display. Small (2 x 2 inch) multi-element arrays on flat substrates have already been developed. The design and analysis techniques employed can be extended to apply to the large field of view, curved on flat substrate head-up display.

8.3 Development Schedule for an Advanced HUD

A reasonable development schedule fo.. the advanced HUD is based to a large extent on the future development of the two major technologies: liquid crystals and holographic optics. A postulated development schedule to end up with a flyable breadboard system with the required performance (improvement in accuracy is expected) is shown in Figure 8-2. This schedule is considered the shortest reasonable schedule, consistent with the premise that many technological gains will occur from other research efforts. This schedule is based on development of the baseline design configuration described in Section 7.0. This system utilizes a flat holographic combiner and 6 x 8 inch nematic reflective liquid crystal on MOS LSI substrate with a thallium arc light source. A curved combiner, transmissive liquid crystal and silicon on sapphire technology and the more efficient diffused light source HUD design would lengthen the schedule.

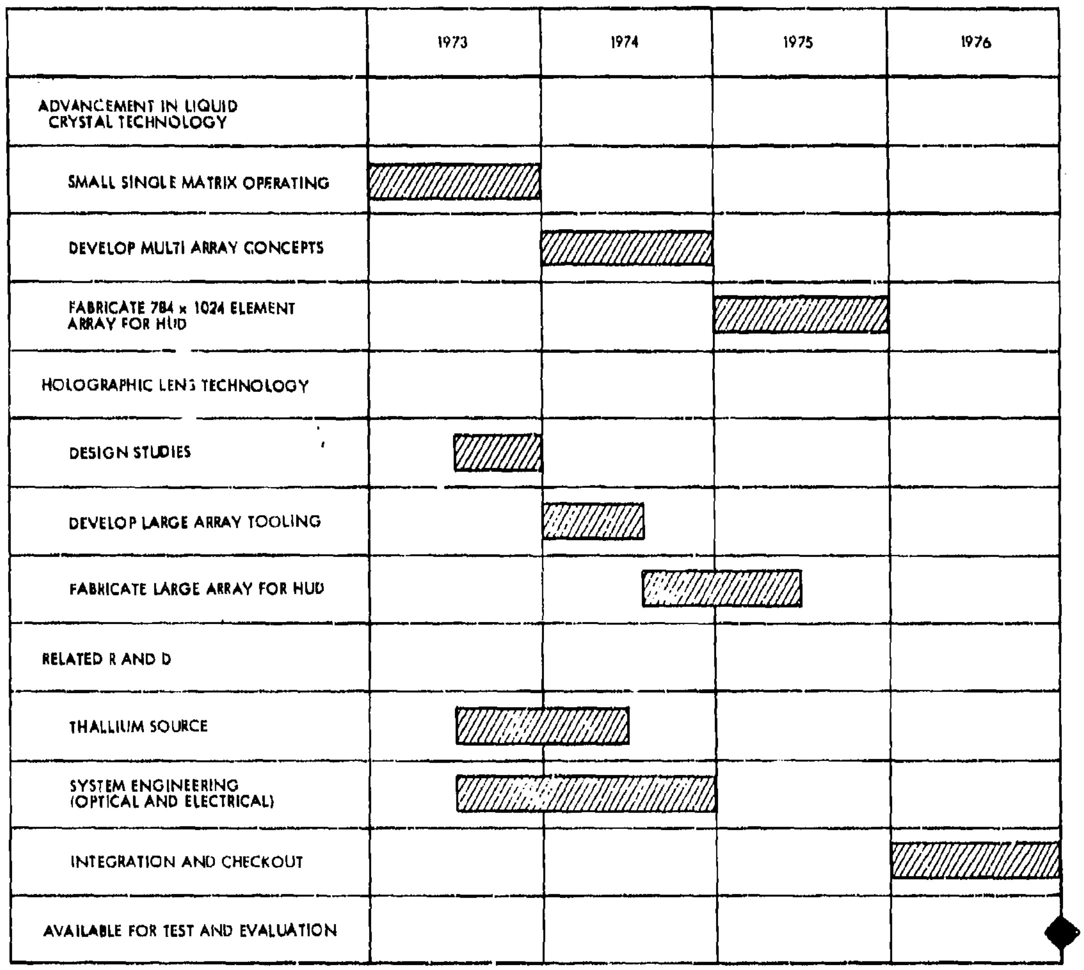


Figure 8-2. Logical development schedule for advanced head up display.

In the area of liquid crystal, it is anticipated that a 100 x 100 resolution matrix will be operating by 1974. The development necessary to provide a multi-matrix array (768 x 1024 elements) will take at least another year. Included in this development is improved high temperature performance and sealing techniques which will allow operation in military aircraft. The holographic optics technological advancements must be made in the areas of developing better computerized design and analysis techniques to improve accuracy, and the development of tooling to fabricate large multi-element arrays. The only other area of required and development research is the thallium arc point source with a high efficiency power supply. This is a minimal risk item which should be possible within a year. In parallel with development in the technology areas, the optical design, detailed electrical design, and interface definition necessary to incorporate the advanced HUD into a particular airframe for flight test evaluation can be achieved. If this is done properly, a flight test could be a reality by late 1976.

APPENDIX A. HUD DEMONSTRATION DEVICES

To demonstrate the basic concept of the advanced head-up display described in this report, a demonstrator was developed to illustrate the principles of the liquid crystal reflective display in conjunction with the holographic lens. As seen in Figure A-1, a projector light source is used to illuminate the reflective liquid crystal matrix element. In order to provide light of the required wavelength and spectral bandwidth, a filter is used in front of projection light source. The liquid crystal matrix is used in a specular reflective mode to maximize brightness of the symbology.

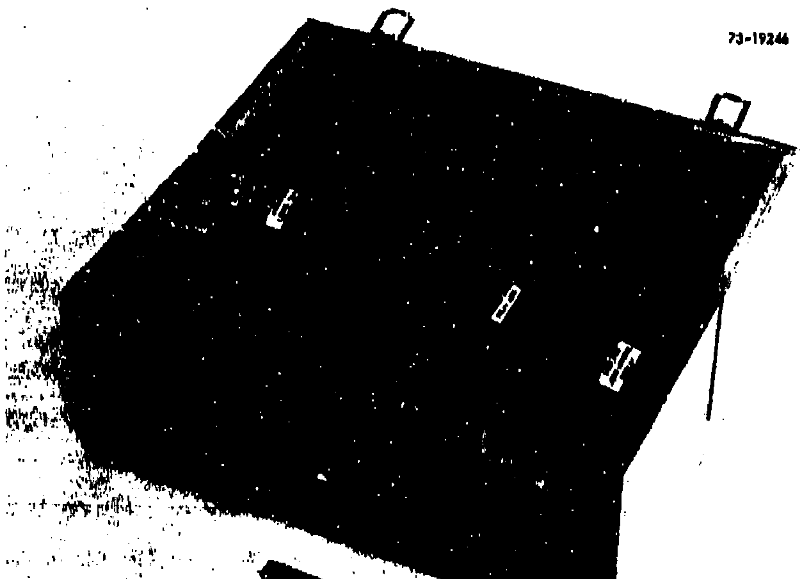


Figure A-1. Advanced HUD concept demonstrator.

In order to minimize first surface reflection from the liquid crystal reflective array, a prism is bonded to the front surface. A relay lens is used to project the liquid crystal image on the holographic lens/combiner. The holographic lens does provide some undesired first surface reflections. Attempts to apply an antireflect coating were discarded due to the possibility of destroying the lens. The lens was made to be responsive to light at 4900 Å with approximately 100 Å bandwidth at 50 percent response. The focal length is 4 inches with a required off axis angle of approximately 17 degrees. Due to its small size (1.5-inches diameter) and the fact that it is a single element holographic lens, the exit pupil and field of view are limited to a small area.

To simulate the reflective liquid crystal matrix, a mirror was etched to provide the reflective HUD symbology pattern as viewed through the holographic lens/combiner. A ceramic plate behind the mirror provided the diffuse scattering. This can ultimately be replaced with a liquid crystal matrix when the state of development is such that a deliverable array can be produced. A photograph of the completed demonstrator is shown in Figure A-1.

A-1 Advanced HUD Mockup

To indicate how the holographic lens/combiner and liquid crystal source can be integrated into an aircraft, a wood and plexiglass mockup was fabricated. This mockup is shown in Figure A-2. The nonfunctional mockup is a one-half size representation of the forward canopy section of the A-10 close air support aircraft. This aircraft was selected because of its large canopy and over the nose visibility (>20 degrees).

The illumination source configuration is a more advanced concept than that defined as the baseline. Instead of a reflective liquid crystal matrix display with a point source collimated light source, the mockup shows a transparent liquid crystal array illuminated from behind by a diffuse light panel source. The 3 x 4-inch array mockup of the source was fabricated using lucite plastic plates. A block 3-x 4-x 1-inch thick is used to represent the light source. The relay lens in front of the liquid crystal plane is represented as being a 3 x 4-inch flat transmissive holographic lens.

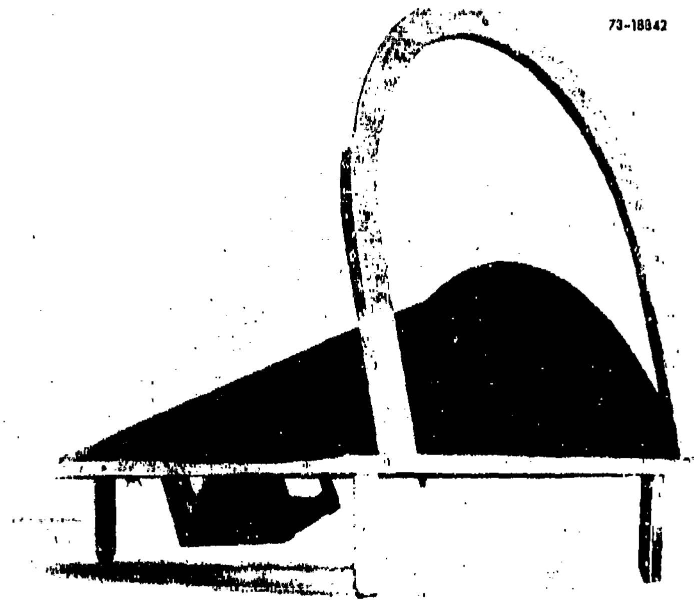


Figure A-2. Advanced HUD mockup.

To provide maximum flexibility, two alternate configurations can be demonstrated with the single mockup. The curved canopy combiner/lens arrangement requires placement of the liquid crystal array between the canopy supports immediately ahead of the instrument panel. The alternate configuration utilizes a flat combiner supported by the canopy structure. This requires the source to be located just below the cowling line at the front of the canopy.

APPENDIX B. HEAD-UP DISPLAY USER SURVEY

During the contract period a Head-Up Display User Survey was performed to obtain HUD design requirements data from the user's (pilot's) standpoint and to take advantage of the operational experience gained by pilots using a HUD. Since the A-7 was selected as the representative aircraft system in which the Hughes HUD requirements would be conceptually examined, it was decided to concentrate the survey efforts on pilots experienced in that aircraft. In all, 17 highly experienced pilots were administered the survey, a blank copy of which is contained in Appendix B. The estimated average total flying time of these pilots was 2,216 hours (330 to 4100 hours). Their average total A-7 HUD time was 284 hours (75 to 800 hours).

The results of the survey are consolidated in the following survey. This Table is developed in the same general format as is the basic survey questionnaire with the questions askea preceding the answers. Where responses are indicated by numbers (i.e., 17, 15, 3, etc.), they represent the number of pilots responding to the question that was asked. Where comments are called for, the actual responses of the pilots are preserved in a consolidated list. Comments, where appropriate, are keyed to the question to which a response is given.

The use of the individual pilot comments should be used carefully, since they do not always represent a concensus or majority opinion, but often they are only an individual's feelings. There was one concensus that should be noted here, and strongly, and that was the unanimous response of YES to the question, "Based on your experience using the HUD, do you believe that the HUD is a useful instrument?" It should also be noted that the high acceptance of the HUD by this group of pilots is almost totally bounded

by their experiences using the A-7D HUD. Several expressed verbal concern that any new HUD developments incorporate as many of the A-7D features as possible.

HEAD-UP DISPLAY USER SURVEY
(Consolidation)

Users: 17 A-7D Pilots

Total Estimated Flight Hours (Average): 2,216 (330 to 4100)

A-7D HUD Hours (Average): 284 (75 to 800)

Other Aircraft HUD Hours: Essentially None

Flight Simulator HUD Hours (Average): 20 (0 to 50

A. During which phases of a mission do you use the HUD ?

Takeoff	14
Landing	17
Enroute Navigation	15
Air-to-Air Weapon Delivery	11
Air-to-Ground Weapon Delivery	17
Rendezvous	7
Stationkeeping	5
Refueling	6
TF/TA	16

Comments: 1. "Angle of attack indication and angle of approach most valuable" (Ref. Landing).

2. HUD is always of value whenever a specific altitude is required (e.g., by placing the Flight Path Marker on the 0^{o} pitch line the aircraft is placed in straight and level flight). (Ref. all of A above.)

B. During each mission phase, how would you rate the usefulness of the HUD?

	High		Medium		Low	
	Day	Night	Day	Night	Day	Night
Takeoff	4	10	7	3	5	3
Landing	15	15	2	1	-	-
Enroute Navigation	3	3	9	8	4	3
Air-to-Air Weapon Delivery	6	5	3	2	3	3
Air-to-Ground Weapon Delivery	17	16	-	1	-	-
Rendezvous	1	2	5	4	9	8
Stationkeeping	1	1	-	-	8	8
Refueling	2	2	-	-	10	10
Terrain Following/ Terrain Avoidance	8	8	6	6	1	1

C. (1) Have you every turned off the HUD (or dimmed the symbology below your visual threshold) because it interfered with the performance of your duties?

YES 10

NO 6 NO Qualified 1

Comment: (Ref. qualified NO): "However, I have turned off selected symbologies I considered obstructive or irrelevant."

(2) If YES, indicate the missions phase(s) and reason(s) for turning the HUD off.

(a) Mission Phase: Attack

1. "Even the DIM setting too bright to see target." (Night Gunnery).
2. "To pick out targets in air or on ground." (Night).
3. "Manual Bombing — Too much garbage."
4. "Sometimes too much information presented in early stages of use, confuses the pilot. This would be to use just the standby pipper, especially during strafe."
5. "Turn off scales (Hdg., Airspeed, and Altitude) because they clutter the HUD when I want to see attack symbology only."
6. "For manual strafing there is too much unncessary symbology."
7. "Too much symbology — too distracting." (Manual Bombing).

(b) Mission Phase: Join-Up

1. "I want my view of the plane I'm rejoining on to be clear. The only info needed is airspeed and it can be obtained from the cockpit easily."
2. "Puts Extra lights in field of view — makes it harder to maintain sight of lead at long distance out." (Night).

(c) Mission Phase: Air Refueling

1. "The HUD is distracting when clearing for other aircraft or looking for a ground reference at night. Never use HUD for refueling operations." (Night).

(d) Mission Phase: GAN – Enroute at Night

1. "The tendency of HUD to be overbearing and predominant, either in seeing all of ground flares or seeing other aircraft, difficulty in adjusting fineness of lighting (level)."

(e) Mission Phase: Tactical Formation and Close Trail

1. "Both phases require strict flying off another plane and the HUD doesn't help in either case. Also in tactical your visibility needs to be uncluttered to look for other planes."

D. List the mission phases during which you would like to use the HUD but cannot at the present time.

1. "Should have air-to-air sight that works. Don't trust TF or TA."
2. "Enroute Nav"
3. "Would like to use the HUD also during mission phases when the pilot must look out the side or top of the aircraft."

E. (1) In bright sunlight, with the HUD at full brightness, can you clearly see all of the displayed symbology?

YES	11	YES Qualified	2
NO	4		

Comments: (YES Qualified)

1. "If displaced at all from the sun."
2. "At most times, depends on sun positions."

(2) If NO, check the type of symbology that are particularly difficult to see:

Numerics	-
Scales	-

Reticle -

Standby Reticle -

Other 1. "Some aircraft all symbology too DIM looking into sun."

All symbology 4

(3) If any of the above is checked, check the reason for the legibility problem:

Symbology not bright enough 4

Symbology jitters -

Symbology not collimated -

Symbology too small -

Display too cluttered -

Other 1. "Sun brighter."

(4) To what extent does sun position influence legibility?

Greatly 2

Moderately 5

Little 9

Not at all -

(5) If sun position is a significant detriment to legibility describe the conditions.

1. "Reflected sun is worse than direct sun."
2. "When flying directly toward sun."
3. "Only when flying directly into bright sun."
4. "Only time it has any effect is if you are aimed directly at the sun."

5. "Only looking directly at the sun."

6. Sun "wash out all symbology."

7. "When bright sun or the sun's rays reflect on the HUD combining glass no symbology can be seen."

8. "When sun is 12 o'clock high."

(6) To what extent does flying in and out of areas of bright sunlight or areas of subdued light influence legibility (e.g., flying under a partial overcast)?

Greatly	1
Moderately	3
Little	6
Not at all	7

(7) If (6) above is a significant problem explain the effects.

1. "Automatic brightness control." (Ref. Not at all).

2. "Must readjust rheostat." (Ref. Moderately).

3. "If bright sunlight is reflected on the combining glass that image makes the information on the HUD unusable." (Ref. Greatly).

F. (1) At night with the HUD dimmed to a comfortable viewing level, does the symbology brightness interfere with seeing and identifying objects in the aircraft external scene such as targets, terrain features and identification points?

Greatly	2
Moderately	8
Little	5
Not at all	2

(2) If your answer to (1) is Greatly or Moderately, describe conditions.

1. "If adjusted properly no problem at all." (Ref. Little).
2. "Night Gunnery with no flares." (Ref. Greatly).
3. "Most problem when viewing against a background of lights — cities, etc., low stars — then try to pick out an aircraft for rejoin or avoidance." (Ref. Moderately).
4. "Trying to find DIM lit ground targets." (Ref. Greatly)
5. "It tends to obscure the target as slant range increases, i.e., hard to get definite target designation." (Ref. Moderately)
6. "It must be adjusted on final depending on the amount of flare light." (Ref. Moderately)
7. "Only when flying over a city with a concentration of lights — tends to lose symbology." (Ref. Little)
8. "Due to sensitivity of adjustment knob - difficult to fine tune light level at night." (Ref. Not at all)
9. "The HUD symbology is distracting when attempting to identify ground features." (Ref. Moderately)
10. "With air illumination the HUD has to be turned up to see the symbology which causes interference with locating ground targets." (Ref. Moderately)

(3) If (1) above is a problem do you have a technique you use (or a suggestion) to minimize the problem? If so please explain.

1. "I turn the HUD off until I have identified the target and am ready to commence my attack." (Ref. Moderately) (Goes with comment (2) 9 above).

2. "Fine tune knob for night lighting." (Ref. Moderately)(Goes with comment (2) 8 above).

3. "Adjust brightness." (Ref. Little)(Goes with comment 7 above)

4. "Put red filter instead of orange." (Ref. Moderately).

5. "I use the green color at night on range instead of the amber night filter. Use the amber filter at night at other times." (Ref. Moderately) (Goes with comment (2) 5 above).

6. "Turn HUD off – change day/night filter." (Ref. Greatly) (Goes with comment (2) 4 above).

7. "HUD dims well to a certain point, then seems to be either off or on dimmer could perhaps be adjusted so to give full dimming control all the way to off. As it is now, if there is a problem, I turn it off." (Ref. Moderately) (Goes with comment (2) 3 above).

8. "Use as dim as possible. Still a problem." (Ref. Greatly) (Goes with comment (2) 2 above).

9. "Night ground attack, I don't use the filter, use normal green symbology." (Ref. Little) (Goes with comment (2) 1 above).

(4) At night with the HUD dimmed sufficiently for comfortable viewing, can you clearly see all of the displayed symbology?

YES	16
NO	1

(5) If NO, check the type of symbology that are particularly difficult to see:

Numerics	-
Scales	1

Reticle ___-___

Standby reticle ___-___

Other _______________-_______________

All symbology ___-___

(6) If any of the above is checked, check the reason for the legibility problem:

Symbology jitters ___-___

Symbology not collimated ___-___

Symbology too small ___-___

Display too cluttered ___-___

Other _______________-_______________

(7) Do you insert the filter into the field of view when using the HUD at night?

YES ___12___ YES Qualified ___3___

NO ___2___

(8) If NO or YES Qualified, why?

1. "Night ground attack, I do not use the filter, use normal green symbology." (Ref. No) (Same comment as F.3.9).

2. "Green color is easier to dim to a very low level – also, easier to see green against light of city during approaches, etc." (Ref. NO)

3. "I like the green – Its a different color from yellow ground lites and makes it easier to discern which is which." (Ref. YES Qualified)

4. "If there is a predominance of orange light on the ground it is better to use green symbology and vice versa." (Ref. YES Qualified)

5. "I use the green color at night on range instead of the amber filter. Use the amber filter at night at other times." (Ref. YES Qualified) (Same comment as F.3.5).

G. (1) Does viewing the outside world through the HUD combining glass cause problems? If yes indicate the time of day. If no problem leave blank.

Dawn	1	Dusk	2	Note: 5 of 17 pilots responded.
Midmorning	1	Night	4	
Midday	1	Always	-	
Midafternoon	1			

(2) Comments

1. Night – "This is only an occasional problem, but with certain combinations of HUD symbology intensity, cockpit lighting intensity, and outside ground lights, there are spurious reflections on the glass. However these are easily identified."

2. "Midmorning, Midday, Midafternoon – Get bad reflections off the lens not the combining glass."

3. "The part is outstanding."

4. Night – "Once again I prefer flying with HUD off when on the wing (flying formation) at night or when flying cross-country."

5. Dawn, Dusk, Night – "Only when trying to keep A/C lights in sight at long distances."

(3) If any of the above items are checked, check the reason for the viewing problem: (Note: Only 4 pilots identified reasons. Others were satisfied with system.)

	Dawn	Midmorn.	Midday	Midaft.	Dusk	Night	Always
View of outside word is distorted							
Color of outside world is changed							
Reflections off the combining glass.		1	1	1		1	
Brightness of the outside world is greatly reduced.					1	1	
Others (identify below)							
(a) Makes it more difficult to see lights	1				1	1	
(b)							
(c)							

H. Can you clearly see or read the HUD labels, indicators and readouts (other than the symbology presented on the combining glass)?

	Daylight		Night	
	Yes	No	Yes	No
In Range Indicator	5	11	11	5
Panel Light Switches	15	1	15	1
Standby Reticle control	16	-	16	-
Test Switch	16	-	16	-
Mils Indicator	16	-	13	3
Standby Reticle Depression Knob	16	-	15	1
Barometer Altitude Radar Switch	16	-	15	1
Filter Knob	16	-	16	-
Scales Switch	16	-	15	1
HUD Brightness Control	16	-	16	-

Comment: (Ref. Night Yes column). "This is O.K. as long as there are good cockpit lights."

I. State below any further observations, opinions, or recommendations concerning the legibility or viewability of the HUD:

1. "The knob (Standby Reticle Depression Knob) in the A-7 is too small and can be difficult to turn. To get large mils depression it takes too much turning."
2. "When using a computed attack the aiming symbol should be limited in travel so that it does not disappear from the field of view especially with INS drift. Then at lest, the pilot knows where the system thinks it is, and corrections can be made."

3. "In strong crosswinds a wider field of view would be useful, also when rolling in on a target aiming refinement could be commenced earlier."

4. "In range indicator useless in present configuration. Mils indicator usually unreadable without additional light source at night."

5. "The FPM (Flight Path Marker, i.e., velocity vector) will drift out of view in landing pattern while turning base leg with a tailwind. When this occurs, you can not determine your angle attack. All symbology should remain in field of view at all times. Pitch lines and FPM may be allowed to drift to far side of HUD and then stay there until information predicts back within field of view."

6. "For teaching the HUD is a super aid, but as with anything, we must caution continually against over dependence."

7. "Never use in range indicator."

8. "I find the HUD is an excellent aid in the cockpit. However, to clearly view and interpret the altitude and airspeed scales I must move my head to one side or another at times. Therefore, I rely on cockpit altitude and airspeed instruments. I believe the HUD would be better if the altitude, airspeed and velocity scales were removed and that all that was left was heading."

J. (1) Is the instantaneous HUD field of view in the aircraft you are currently flying adequate with respect to horizontal and vertical coverage?

YES	13
NO	4

(2) If NO, what should the field of view size be?

Horizontal, ________ degrees

Vertical, ________ degrees

Note: Only one response here and it was for +10 degrees horizontal

(3) Reasons for your choice in (2) above.

1. "If it could be done, any increase in size of view would be helpful. During conditions of high winds, or high "Gs" HUD symbology is sometimes very hard to pick up without moving head."

2. "I personally can view everything I need to view through the HUD."

3. "I would like to be able to slew aiming symbol to targets more off the center line of the aircraft. Would not have to be aimed so directly at the target to designate."

4. At high angles of attack (landing phase), it is necessary to raise seat height to see flight path marker."

(4) If the HUD field of view were adjustable please indicate whether you would recommend a larger or smaller size for the following mission phases. (Base your responses on the field of view provided in the aircraft that you are flying.) (Note: Responses were mostly check marks. Those that were given are shown beneath the number of responses.)

	Larger		Smaller	
	Degrees Horiz.	Degrees Vert.	Degrees Horiz.	Degrees Vert.
Takeoff	-	2 15°		
Landing	1	4 10°, 15°	-	-
Enroute Navigation	2 10° x 2	-	-	-
Air-to-Air Weapon Delivery	4 25°	4 5°, 10° x 2		
Air-to-Ground Weapon Delivery	8 30°, 40° 10°, 15° x 2	3	-	-
Terrain Avoidance/ Terrain Following	-	-	-	-

Comments: 1. "A-7D HUD is adequate as is. Field of view should be as large as possible commensurate with size of center windscreen of fighter."

K. (1) What is your choice for a HUD vertical field of view point of reference relative to the longitudinal axis of the aircraft?

Armament Datum Line	-
Flight Reference Line -- Fixed	1
Flight Reference Line -- Adjusted for Trim	-
Velocity Vector	14
Center of the Display	-
No Opinion	2

(2) What is the reason for your choice?

1. "Having anything in the HUD other than the Flight Path Marker (Velocity Vector) change relative position because of drift, causing an uncomfortable sensation."
2. "Velocity vector represents vector of aircraft."
3. "Similar to the A-7D, whatever that is, but slightly extended on bottom side of the field of view."
4. "Easier to visualize and interpret information." (Ref. Flight Reference Line-Fixed).
5. "You are always concerned with where the aircraft is going in all phases of flight. Any other position would make viewing more difficult." (Ref. Velocity Vector).
6. "Present system and it works super." (Ref. Velocity Vector).
7. "To give equal distance above and below the velocity vector in the display."
8. "Where the aircraft is going is of primary importance. In the A-7D HUD other information moves about the flight path marker (Velocity Vector) and this is ideal."
9. "I want my velocity vector to be constantly displayed. Almost any other reference would detract from the velocity vector value. Also, I find velocity vector most useful of all symbology."
10. "You can see all sides of your projected impact point." (Ref. Velocity Vector).
11. "I like to see everything by looking the way I am going. Our scales should move with velocity vector in azimuth or we don't have Flight Path Marker mixed with scales."

12. "The velocity vector of the aircraft represents the flight path of the aircraft which tells me where I am going and pretty well where forward firing ordnance is going."

13. "My main interest is where the aircraft is going." (Ref. Velocity Vector).

(3) Using your choice for a HUD vertical field of view point of reference, indicate for each of the mission phases and modes listed below, where it should be placed relative to the longitudinal axis of the aircraft.

	On	Above	Below	Not Applicable
Takeoff	6	4	1	1
Landing	5	1	4	1
Enroute Navigation	9	1	1	1
Air-to-Air Weapon Delivery	5	2	1	3
Air-to-Ground Weapon Delivery	2	1	7	2
Rendezvous	4	-	-	5
Staionkeeping	4	-	-	3
Refueling	3	2	-	5
Terrain Avoidance/ Terrain Following	10	-	1	2

L. (1) During the course of a mission, do you find it necessary to adjust the HUD brightness?

Often	-
Sometimes	11
Rarely	4
Never	-
Often (night)	1/2
Rarely (day)	1/2
Never (Qualified)	1

(2) If often or sometimes, why?

1. "It can be too bright for gunnery where symbology interferes with target identification and target designation." (Ref. Sometimes).
2. "Only major adjustments needed at night." (Ref. Sometimes).
3. "Difference between nominal darkness and approach lights for landing, flares on range." (Ref. Often (night) and Rarely (day)).
4. "Due to change in brilliance of sun (clouds, etc.)." (Ref. Sometimes.)
5. "Mostly at night, or if automatic sensors malfunction." (Ref. Sometimes).
6. "According to how much of the HUD I want to see and different phases of the mission. All depends on my requirements and not on HUD inabilities." (Ref. Sometimes).
7. "Changing light conditions (position relating to sun)." (Ref. Sometimes).

8. "Don't want it to distract from the target. Too bright and I stare at it." (Ref. Sometimes).

9. "Adjustment is sometimes necessary because of the change in brightness of the sun's light." (Ref. Sometimes).

10. "If HUD used specific information ready at a glance. I have it turned up higher than normally." (Ref. Sometimes).

11. "Only at night." (Ref. Never (Qualified)).

M. (1) Based on your experience using the HUD, do you believe that the HUD is a useful instrument?

YES	17	Comments: 1. "Outstanding"
NO	____	2. YES "X!"
MARGINAL	____	

N. If a new HUD was being designed to your specification, indicate what design features, capability or configuration you would want incorporated?

1. "Remote UHF frequency indication – selectable ON and OFF. Could be very useful."

2. "I would like a HUD the same as the A7-D but with ability to show radio channel and range and bearing to selected target/destruction or TACAN beacon."

3. "Greater reliability – cut down the failures due to overheating. Have selectable scales info., i.e., heading but no altitude or air-speed, or any combination. A fine adjustment on the size of the aiming symbol display. It would be nice if you could get it down to almost a pin point so you could be absolutely sure of the designation point.

4. "With vector velocity reference and ability to 'cage', i.e., keep FPM centered and not affected by wind drift for certain aspects of flight." Mils rotate knob easier to turn. Do away with airspeed in HUD and replace with more useful info, i.e., radio frequency, TACAN Channels, etc."

5. "Some way of presenting bank information when desired. It's not necessary at all times. Use either bank lines or a numerical value, i.e., 30L or 17R for a 30° left bank or a 17° right bank. For this info we need to know the exact angle of bank."

6. "I am ver atisfied with all aspects of the A7-D HUD."

7. "In air to ground auto strafe, all selected symbology is at the same point as the target, therefore it is too congested. Aircraft bank readout in HUD other than that what is currently displayed."

8. "HUD display should not move horizontally with crosswind. Radio frequencies and TACAN channels should be displayed."

9. "Make HUD symbology basic and then allow pilot to call up individual systems on slate. Auxiliary radio frequencies should be seen in HUD. The HUD is outstanding for instrument approaches."

10. "Selectable to show radio channelization. Air-to-Air sight."

11. "All those presently incorporated on the A-7D HUD."

12. "More variable brightness control. Move scales with vector. About 25 percent more azimuth view."

13. "Add the capability to show manual radio channels. Overall, I believe that the HUD is a quantum step forward as an aide to the pilot in the 20th Century."

14.. "I like our's — I would put UHF frequency display."

15. "At least as good as the A-7 HUD, possibly slightly larger. Definitely adjustable field of view."

16. "A more suitable presentation of ILS symbology — it's there now, but I feel of limited value."

APPENDIX C. HOLOGRAM ARRAY GEOMETRY AND DATA PLOTS

C-1 HOLOGRAM ARRAY GEOMETRY AND DATA PLOTS

In this appendix we illustrate the use of the semi-quantitative and qualitative relationships described in Section 4.4 to make preliminary system layouts and choices. This is followed by the actual data plots used in the binocular disparity and distortion analyses.

Figure C-1 shows a typical system utilizing a reflection hologram array as a combiner/projector element. Here the off-axis angle ϕ is 90 degrees and the asymmetry angle ψ is 0 degree. The approximate position and size of the source plane are shown for magnifications of a 4 in.

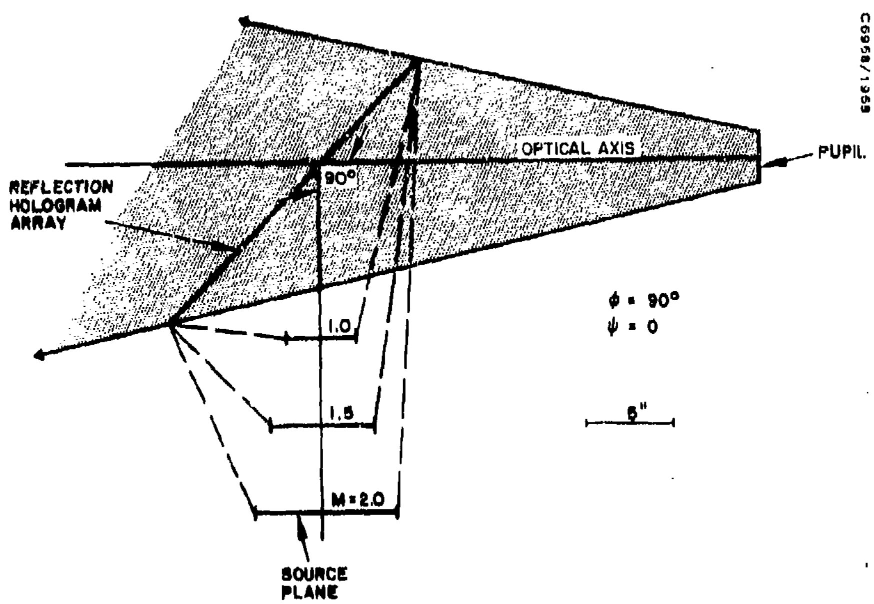


Figure C-1. System geometry using a reflection hologram array/combiner plate with ϕ = 90 and ψ = 0.

square input of 1.0, 1.5, and 2.0. The degree of asymmetry of the extreme rays shown is an indication of the amount of distortion present in the projected image; this correlation has been formed by performing ray-tracing distortion analyses on systems with varying parameters. Therefore, this figure indicates that in general, as the magnification increases, the expected amount of distortion decreases. This trend is offset by other factors, such as system size and/or the requirements for image relay optics.

It is apparent from Figure C-1 that the amount of distortion will decrease as the off-axis angle ϕ is decreased. For example, Figure C-2 shows a system with ϕ = 40 degrees and ψ = -20 degrees. Here there is little image distortion indicated, but the amount of field distortion, as indicated by the variable array area per unit solid angle of the field of view, is quite significant. It should be noted that this distinction between image distortion and field distortion is not precise, but it is qualitatively meaningful for preliminary analysis. The amount of field distortion can be decreased by increasing the asymmetry angle ψ. Minimum field distortion would occur for ψ = ϕ/2 or +20 degrees, but it is evident that this would introduce more image distortion. The intermediate case is the symmetric configuration, with ψ = 0, shown in Figure C-3.

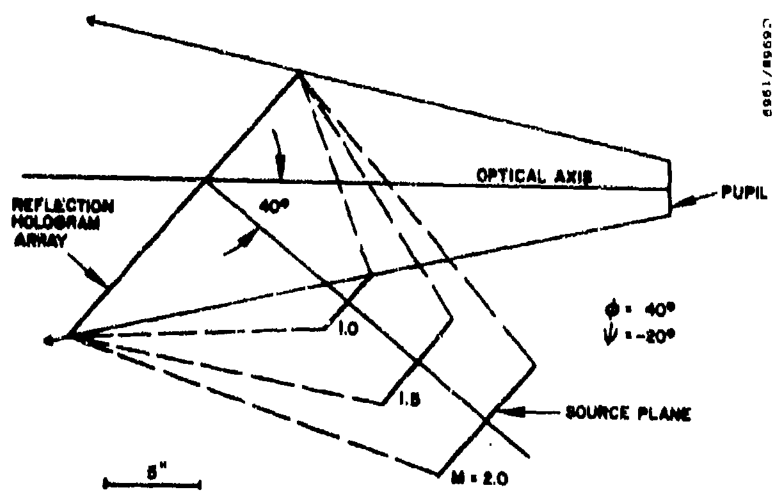


Figure C-2. System geometry using a reflection hologram array/combiner plate with ϕ = 40 degrees and ψ = -20 degrees.

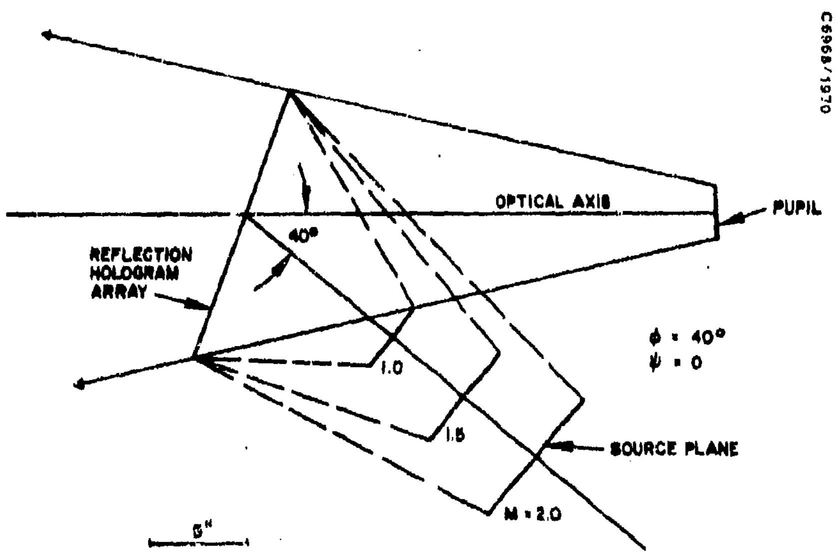


Figure C-3. System geometry using a reflection hologram array/combiner plate with ϕ = 40 degrees and ψ = 0.

Both types of distortion can be minimized by choosing the smallest off-axis angle allowed by the basic system geometry. The minimum angle depends on the system parameters and the required relay optics. For example, in the system under consideration here, an off-axis angle of ϕ = 18 degrees just allows the lower extreme ray to leave the line-of-sight volume for M = 1.0. This is shown in Figure C-4 with the approximate source plane locations and sizes for M = 1.5 and 2.0. It is evident that, for $M < 2.0$, the source plane must be projected into the system by auxiliary optics. An image relay lens to perform this projection should be located with its exit pupil at the image of the viewing pupil formed by the hologram array. This fact and the image magnification determine the relay lens focal length, while the size of the pupil image fixes the aperture of the relay lens and therefore its f/number. For the system of Figure C-4, the f/number required to provide the desired viewing pupil size is rather low and is a strong function of the magnification, M. This relationship is shown in

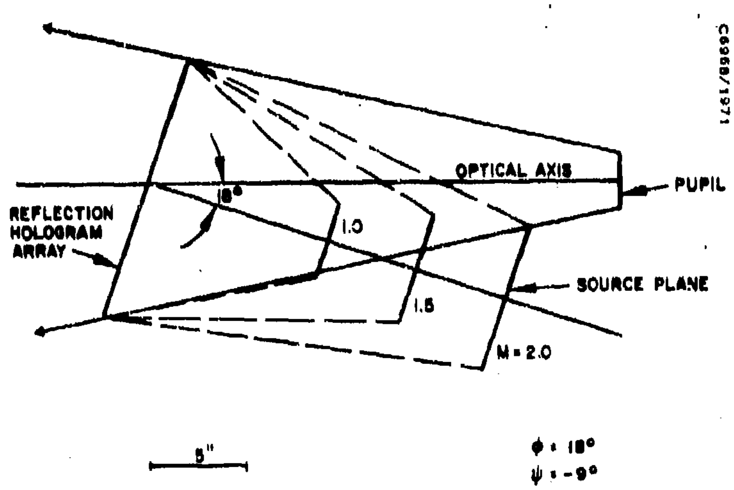


Figure C-4. System geometry using a reflection hologram array/combiner plate with ϕ = 18 degrees and ψ = -9 degrees.

Figure C-5 for a 3-in. pupil and a 5-in. pupil. Based on this data, we would pick a relay magnification of M = 1.4.

C-2 DISTORTION ANALYSES DATA

In this appendix we demonstrate the effect of the off-axis angle ϕ and the asymmetry angle ψ on the average distortion of the image. We also illustrate the use of an offset in the source plane to provide a better use of the array aperture. These data were plotted for 41 x 41 arrays in order to eliminate the local distortion at unaligned intersections in the basic design.

Figure C-6 shows the input to the array. Figures C-7 through C-14 show the corresponding (distorted) output, calculated by interpolating between the array formation points. All output plots show the image that would be seen looking from the center of the pupil plane, on a 100 x 100 degree format.

Figures C-7, C-8, and C-9 show the effect of increasing the maximum design FOV for symmetric arrays (ψ = 0) with f = 250 mm (10 inches) and d = 600 mm (23.6 inches). As the FOV increases from 20 x 20 to 60 x 60 degrees the image changes from a simple linear trapezoidal

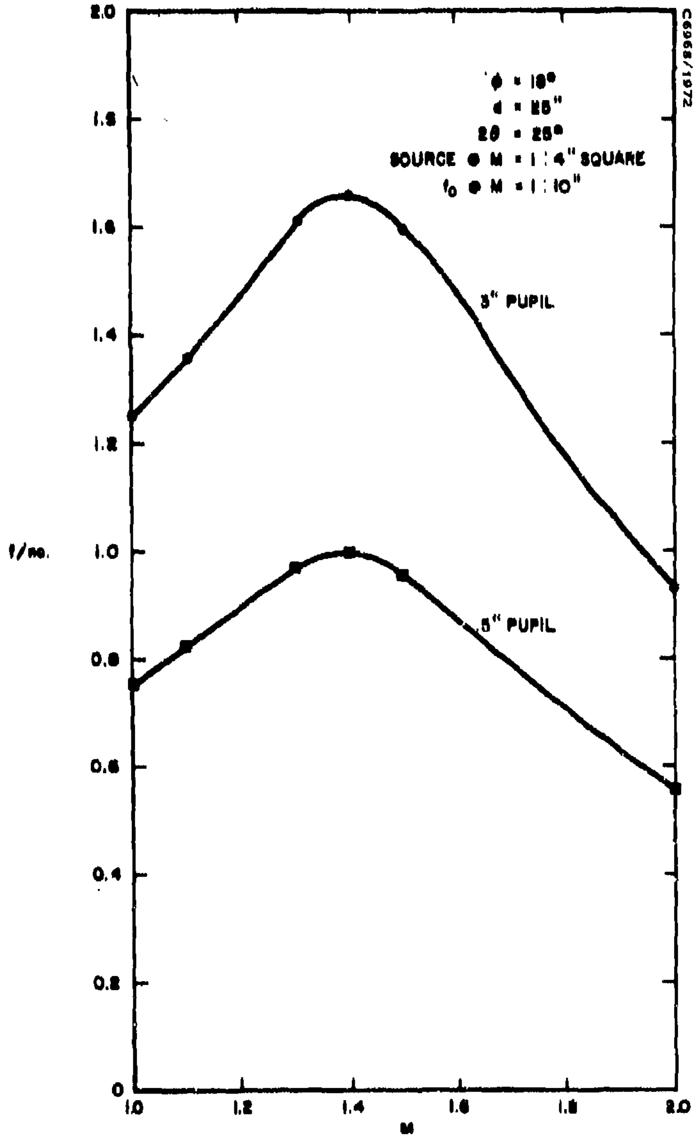


Figure C-5. Relay lens F/number variation with input image magnification.

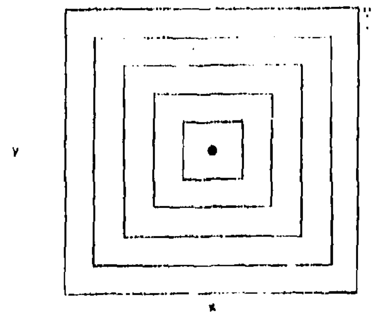


Figure C-6. Array input.

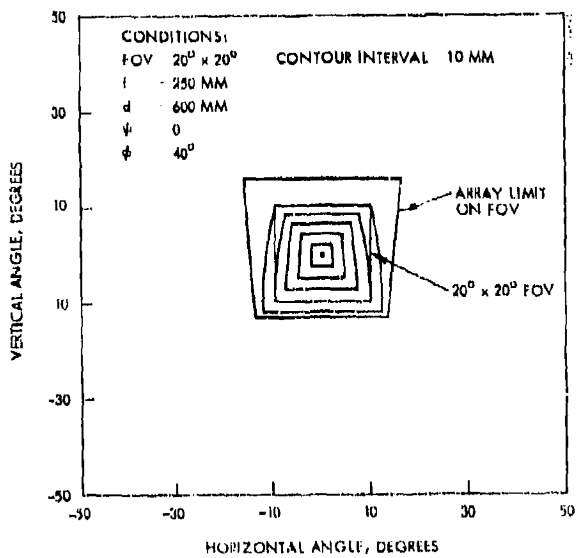


Figure C-7. Array output.

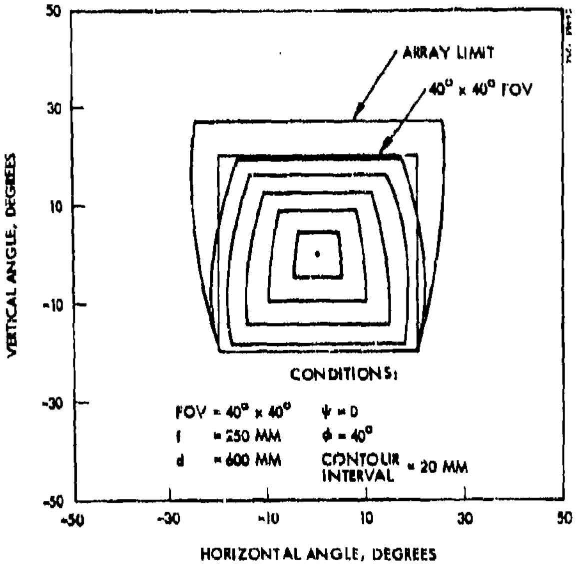


Figure C-8. Array output.

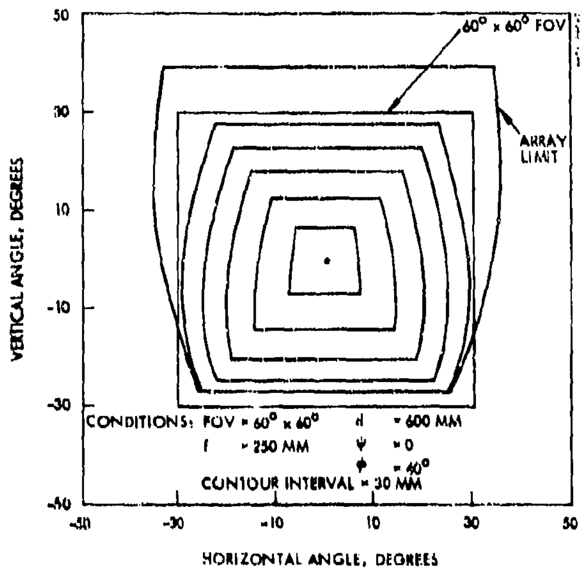


Figure C-9. Array output.

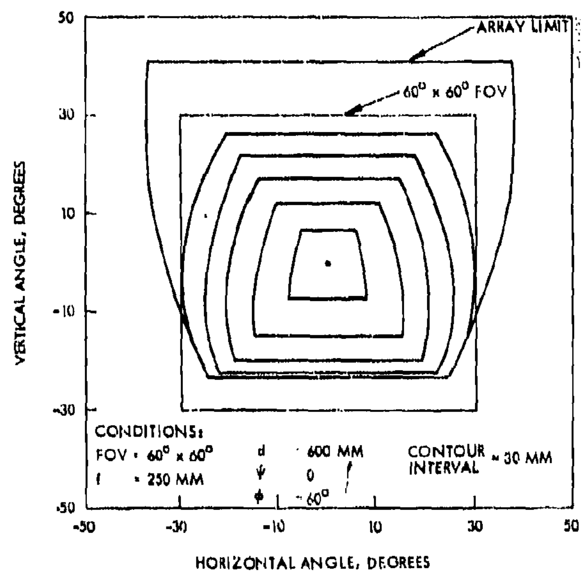


Figure C-10. Array output.

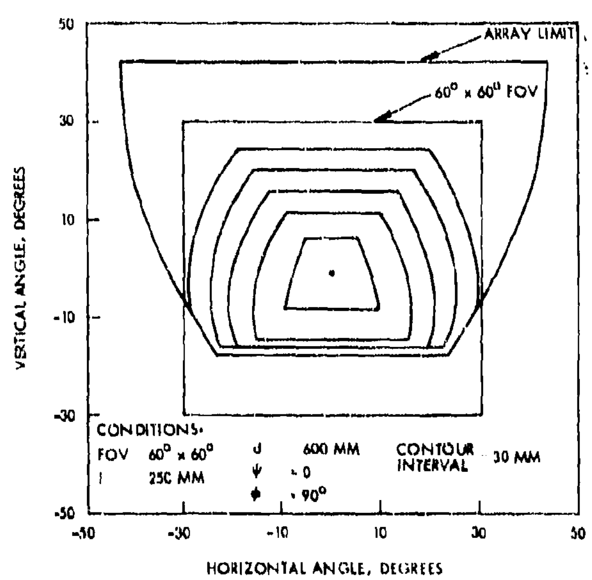


Figure C-11. Array output.

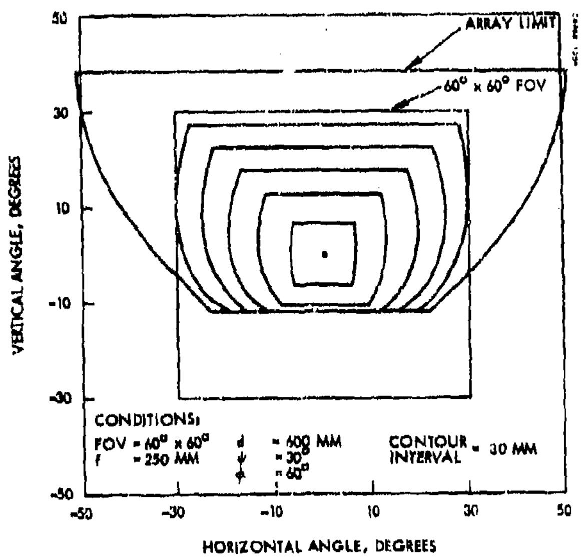


Figure C-12. Array output.

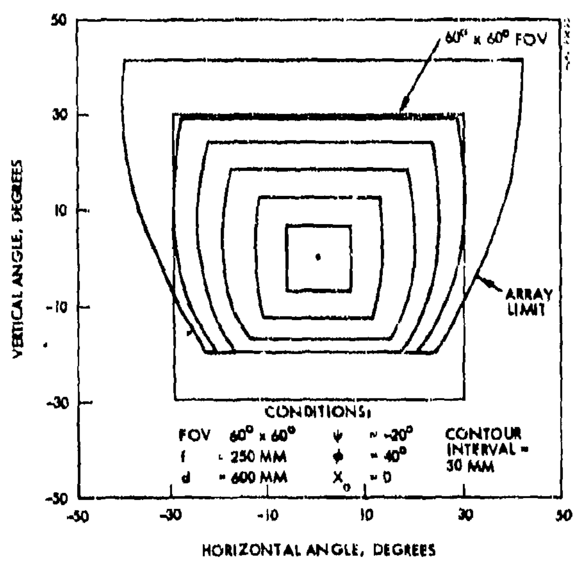


Figure C-13. Array output.

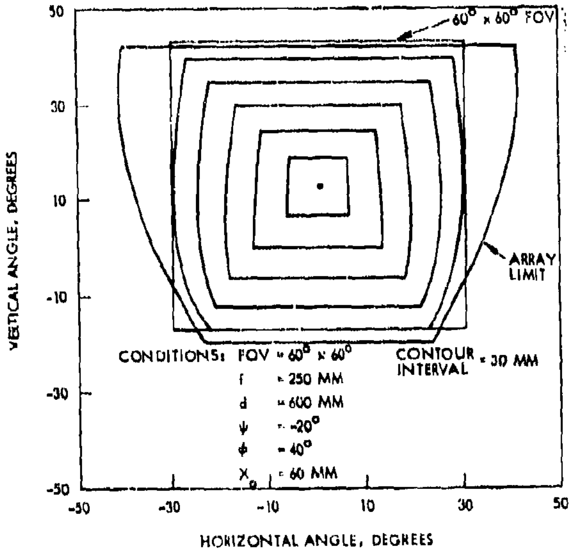


Figure C-14. Array output.

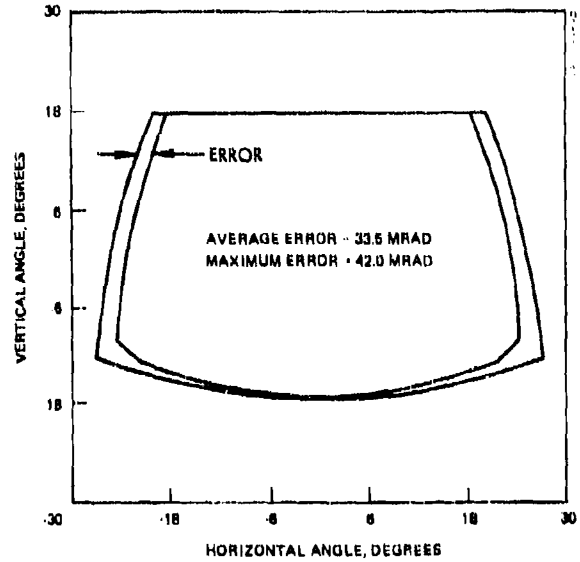
distortion to a nonlinear trapezoidal distortion. The increased nonlinearity of higher off-axis angles is shown in Figure C-10 for ϕ = 60 degrees and Figure C-11 for ϕ = 90 degrees, with other parameters held constant.

The "image" distortion can be decreased, with a resulting increase in "field" distortion, by tilting the array toward the source plane, i.e., negative ψ. This effect is shown in Figure C-12, which is otherwise the same as Figure C-10 (ϕ = 60 degrees).

Finally, the "field" distortion resulting from the negative ψ can be partially compensated by moving the input relative to the array. This technique is illustrated in Figures C-13 and C-14 for ϕ = 40 degrees, ψ = -20 degrees. In Figure C-13 there is no offset, while in Figure C-14 the source is offset by 60 mm.

C-3 BINOCULAR DISPARITY DATA

Figure C-15 represents the binocular disparity plot for a single element line with a 45 degree horizontal image for 68 mm interpupillary



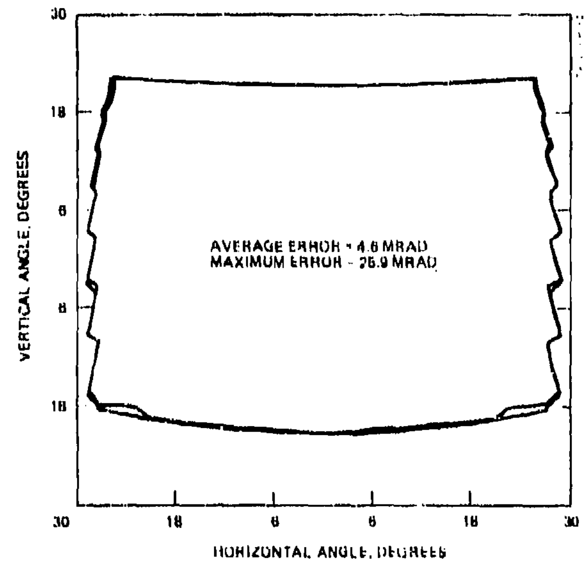
Provides data for ⊡ points at 45.2 degrees in Figure 4-31. Input image width 390 mm.

Figure C-15. Binocular disparity plot for single element at 45.2 ave horizontal FOV, for 68 mm interpupillary distance, at ▲▲ points in Figure 4-23.

distance. Referring to Figure 4-23 this is at the ▲▲ points. This provides the data for the ⊡ points at 45 degrees in Figure 4-31.

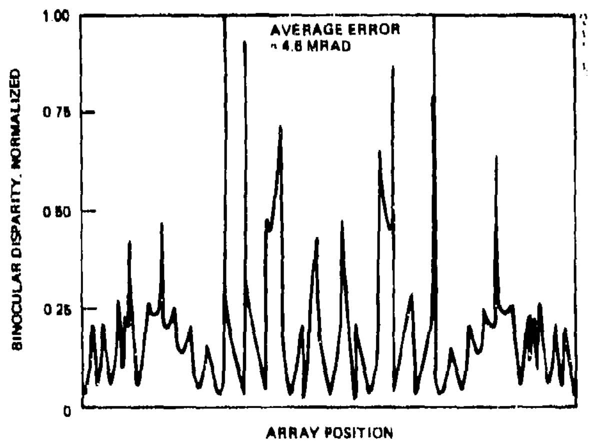
Figure C-16 is the binocular disparity plot for a 5 x 11 element array with a 56.5 degree horizontal image for 68 mm interpupillary distance at the ▲▲ points in Figure 4-23. This provides data for the ⊝ points at 56.5 degrees in Figure 4-31.

Figure C-17 is a linear plot of the binocular disparity for the 5 x 11 element array in Figure C-16. It is normalized to a maximum error of 25.9 mrad. Curves starts at upper center of Figure C-16 and continues clockwise with peaks at unaligned intersections.



Provides data for (.) points at 56.5 degrees in Figure 4-31. Input image width 390 mm.

Figure C-16. Binocular disparity plot for 5 x 11 array at 56.5 degrees horizontal FOV, for 68 mm interpupillary distance, at ▲ ▲ points in Figure 4-23.



Linear plot of binocular disparity for 5 x 11 array from data on Figure C-16. Normalized to maximum error of 25.9 mrad. Curve starts at upper center of output plot and continues clockwise. Peaks come at unaligned intersections around image.

Figure C-17. Linear binocular disparity plot.

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
--	Air Force Avionics Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio 45433

13. ABSTRACT

A study of the requirements for and the design of an advanced head-up display (HUD) was conducted. The requirements, based on use in an advanced close air support fighter, included wide field of view (60-x 45-degree), and high brightness (~8,000 fL). The requirements analysis was supported by interviews with pilot users of head up displays in the field. It was concluded that conventional HUD techniques (cathode ray tubes, thick lenses, etc.) could not be practically used to meet these requirements. Accordingly, an advanced design utilizing holographic optics and liquid crystal display techniques was conceived and evaluated. The holographic lens provides the combiner and collimator functions. The liquid crystal matrix display provides modulation of the light from a collimated arc light source to provide either sensor or symbol video. Using these components, several alternate configurations capable of meeting the requirements were derived. The A-10 aircraft was selected as a candidate for the installation due to its large canopy and over the nose visibility. As part of the study program, a demonstrator was developed to indicate how the holographic lens/combiner and reflective liquid crystal can be used together as a see through display. Also a half size mockup of the baseline cockpit configuration was fabricated.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Head-Up Display						
Holographic Optics						
Liquid Crystal Display						